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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 :
H04J 11/00, H04B 10/155

A1

(11) International Publication Number: WO 00/07317

(43) International Publication Date: 10 February 2000 (10.02.00)

(21) International Application Number: PCT/US99/17258

(22) International Filing Date: 29 July 1999 (29.07.99)

(30) Priority Data:
09/127,343 30 July 1998 (30.07.98) US

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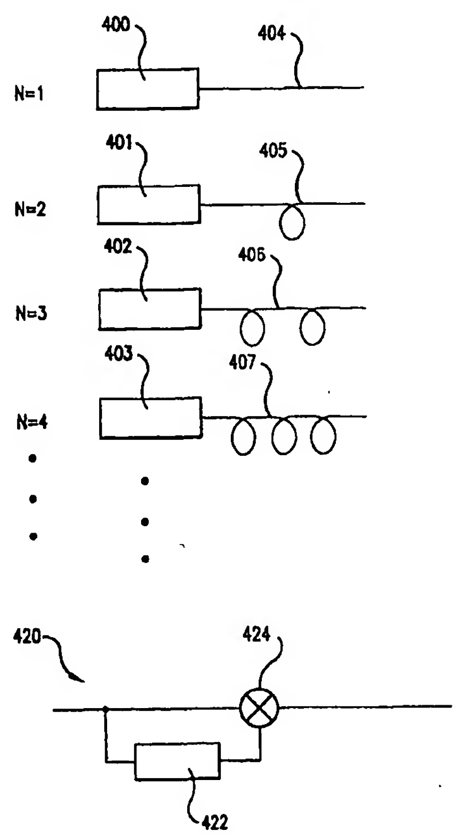
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: METHOD AND APPARATUS FOR REDUCED INTERFERENCE IN OPTICAL CDMA

(57) Abstract

A multi–user optical fiber communications system uses spread spectrum code division multiple access techniques to achieve better bandwidth utilization. Each channel of the system is provided with light source that is temporally and spectrally modulated by an encoder. Modulation is accomplished by first passing the data through a pulse modifier to obtain a stream of shortened pulses with a reduced duty cycle. The modulated light is coupled to a fiber and data are recovered by the decoder. The source includes a superluminescent fiber source that is split multiple times and amplified in a hierarchical manner to produce a plurality of like sources. The like sources are decorrelated by adding delays to the different sources. Each of the encoders includes an encoding mask having a first code that encodes the optical signal. Light, spatially encoded by the mask and temporally modulated with data, is transmitted over a fiber link with the signals of other users and received by a decoder. Within each decoder, a polarization insensitive separator splits the received light into two equal power components which are provided to two decoding masks used to decode the signal. One of the masks has a second code identical to the first code and the other mask has a third code complementary to the first code. The output light beams filtered by the masks are differentially detected to generate an output signal, which is further processed for data recovery. The electrical signal is low pass filtered and electrically square law detected. The first codes are selected from a set of unipolar codes derived from a set of balanced bipolar orthogonal codes. The codes may be either binary or analog.



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METHOD AND APPARATUS FOR REDUCED INTERFERENCE IN OPTICAL CDMA

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to optical communication systems and, more particularly, to optical code-division multiple access communications systems that transmit data over optical fibers.

2. Description of the Related Art

Recent years have seen rapidly expanding demands for communications bandwidth, resulting in the rise of technologies such as satellite communications, video programming distribution networks such as cable television, and spread-spectrum telephony including, for example, code-division multiple access telephony. Such technologies have become common and well integrated into everyday communications. Growing demand for communications bandwidth has brought significant investments in new communications technologies and in new communications infrastructure. For example, the cable television industry, telephone companies, Internet providers and various government entities have invested in long distance optical fiber networks and in equipment for fiber networks. The addition of this infrastructure has, in turn, spurred demand for bandwidth use, resulting in demand for yet additional investment in new technologies and infrastructure.

Installing optical fibers over long distances is expensive. Additionally, conventional optical fiber or other optical communication networks utilize only a small fraction of the available bandwidth of the communication system. There is consequently considerable interest in obtaining higher utilization of fiber networks or otherwise increasing the bandwidth of optical fiber systems. Techniques have been developed to increase the bandwidth of optical fiber communication systems and to convey information from plural sources over a fiber system. Generally, these techniques seek to use more of the readily available optical bandwidth of optical fibers by supplementing the comparatively simple coding schemes conventionally used by such systems. In some improved bandwidth fiber systems, the optical fiber carries an optical channel on an optical carrier signal consisting of a single, narrow wavelength band and multiple users access the fiber using time-division multiplexing (TDM) or time-division multiple access (TDMA). Time division techniques transmit frames of data by assigning successive time slots in the frame to particular communication channels. Optical TDMA requires short-pulsed diode lasers and provides only moderate improvements in bandwidth utilization. In addition, improving the transmission rates on a TDM network

requires that all of the transceivers attached to the network be upgraded to the higher transmission rates. No partial network upgrades are possible, which makes TDM systems less flexible than is desirable. On the other hand, TDM systems provide a predictable and even data flow, which is very desirable in multi-user systems that experience "bursty" usage. Thus, TDM techniques will have continued importance in optical communications systems, but other techniques must be used to obtain the desired communications bandwidth for the overall system. Consequently, it is desirable to provide increased bandwidth in an optical system that is compatible with TDM communication techniques.

One strategy for improving the utilization of optical communication networks employs wavelength-division multiplexing (WDM) or wavelength-division multiple access (WDMA) to increase system bandwidth and to support a more independent form of multiple user access than is permitted by TDM. WDM systems provide plural optical channels each using one of a set of non-overlapping wavelength bands to provide expanded bandwidth. Information is transmitted independently in each of the optical channels using a light beam within an assigned wavelength band, typically generated by narrow wavelength band optical sources such as lasers or light emitting diodes. Each of the light sources is modulated with data and the resulting modulated optical outputs for all of the different wavelength bands are multiplexed, coupled into the optical fiber and transmitted over the fiber. The modulation of the narrow wavelength band light corresponding to each channel may encode a simple digital data stream or a further plurality of communication channels defined by TDM. Little interference will occur between the channels defined within different wavelength bands. At the receiving end, each of the WDM channels terminates in a receiver assigned to the wavelength band used for transmitting data on that WDM channel. This might be accomplished in a system by separating the total received light signal into different wavelengths using a demultiplexer, such as a tunable filter, and directing the separated narrow wavelength band light signals to receivers assigned to the wavelength of that particular channel. At least theoretically, the availability of appropriately tuned optical sources limit the number of users that can be supported by a WDM system. Wavelength stability, for example as a function of operating temperature, may also affect the operational characteristics of the WDM system.

As a more practical matter, the expense of WDM systems limits the application of this technology. One embodiment of a WDM fiber optic communication system is described in U.S. Patent No. 5,579,143 as a video distribution network with 128 different channels. The 128 different channels are defined using 128 different lasers operating on 128 closely spaced but distinct wavelengths. These lasers have precisely selected wavelengths and also have the well-defined mode structure and gain characteristics demanded for communications systems.

Lasers appropriate to the WDM video distribution system are individually expensive so that the requirements for 128 lasers having the desired operational characteristics make the overall system extremely expensive. The expense of the system makes it undesirable for use in applications such as local area computer networks and otherwise limits the application of the technology. As is described below, embodiments of the present invention can provide a video distribution network like that described in U.S. Patent No. 5,579,143, and embodiments of the invention can provide other types of medium and wide area network applications, making such systems both more flexible and more economical. Unlike the WDM many laser system of U.S. Patent No. 5,579,143, embodiments of the present invention may be sufficiently flexible and cost effective to be used in at least some types of local area networks.

Embodiments of the present invention, as described below, use spread spectrum communication techniques to obtain improved loading of the bandwidth of an optical fiber communication system in a more cost-effective manner than known WDM systems. Spread spectrum communication techniques are known to have significant advantages and considerable practical utility, most notably in secure military applications and mobile telephony. There have consequently been suggestions that spread spectrum techniques, most notably code-division multiple access (CDMA), could be applied to optical communications technologies. Spread spectrum techniques are desirable in optical communications systems because the bandwidth of optical communications systems, such as those based on optical fibers, is sufficiently large that multi-dimensional coding techniques can be used without affecting the data rate of any electrically generated signal that can presently be input to the optical communications system. Different channels of data can be defined in the frequency domain and independent data streams can be supplied over the different channels without limiting the data rate within any one of the channels. From a simplistic point of view, the WDM system described above might be considered a limiting case of a spread spectrum system in that plural data channels are defined for different wavelengths. The different wavelength channels are defined in the optical frequency domain and time domain signals can be transmitted over each of the wavelength channels. From a CDMA perspective, the distinct wavelength channels of the WDM communication system described above provide a trivial, single position code, where individual code vectors are orthogonal because there is no overlap between code vectors.

There have been suggestions for optical CDMA systems that are generally similar to traditional forms of radio frequency CDMA, for example in Kavehrad, et al., "Optical Code-Division-Multiplexed Systems Based on Spectral Enoding of Noncoherent Sources," J. Lightwave Tech., Vol. 13, No. 3, pp. 534-545 (1995). As opposed to the WDM system

described above, the suggested optical CDMA system uses a broad-spectrum source and combines frequency (equivalently, wavelength) coding in addition to time-domain coding. A schematic illustration of the theoretical optical CDMA suggested in the Kavehrad article is presented in FIG. 1. The suggested optical CDMA system uses a broad spectrum, incoherent source 12 such as an edge-emitting LED, super luminescent diode or an erbium-doped fiber amplifier. In the illustrated CDMA system, the broadband source is modulated with a time-domain data stream 10. The time domain modulated broad-spectrum light 14 is directed into a spatial light modulator 16 by a mirror 18 or other beam steering optics.

Within the spatial light modulator 16, light beam 20 is incident on a grating 22, which spatially spreads the spectrum of the light to produce a beam of light 24 having its various component wavelengths spread over a region of space. The spatially spread spectrum beam 24 is then incident on a spherical lens 26 which shapes and directs the beam onto a spatially patterned mask 28, which filters the incident light. Light spatially filtered by the mask 28 passes through a second spherical lens 30 onto a second diffractive grating 34, which recombines the light. Mask 28 is positioned midway between the pair of confocal lenses 26, 30 and the diffraction gratings 22, 34 are positioned at the respective focal planes of the confocal lens pair 26, 30. The broad optical spectrum of the incoherent source is spatially expanded at the spatially patterned mask 28 and the mask spatially modulates the spread spectrum light. Because the spectrum of the light is spatially expanded, the spatial modulation effects a modulation in the wavelength of the light or, equivalently, in the frequency of the light. The modulated light thus has a frequency pattern characteristic of the particular mask used to modulate the mask. This frequency pattern can then be used to identify a particular user within an optical network or to identify a particular channel within a multi-channel transmission system.

After passing through the mask 28, the spatially modulated light passes through the lens 30 and the wavelength modulated light beam 32 is then spectrally condensed by the second grating 34. The wavelength modulated and spectrally condensed light beam 36 passes out of the spatial light modulator 16 and is directed by mirror 38 or other beam steering optics into a fiber network or transmission system 42. The portion of the CDMA system described to this point is the transmitter portion of the system and that portion of the illustrated CDMA system down the optical path from the fiber network 42 constitutes the receiver for the illustrated system. The receiver is adapted to identify a particular transmitter within a network including many users. This is accomplished by providing a characteristic spatial mask 28 within the transmitter and detecting in the receiver the spatial encoding characteristics of the transmission mask from among the many transmitted signals within the optical network. As

set forth in the Kavehrad article, it is important for the mask 28 to be variable so that the transmitter can select from a variety of different possible receivers on the network. In other words, a particular user with the illustrated transmitter selects a particular receiver or user to receive the transmitted data stream by altering the spatial pattern of the mask 28, and hence the frequency coding of the transmitted beam 40, so that the transmitter mask 28 corresponds to a spatial coding characteristic of the intended receiver.

The receiver illustrated in FIG. 1 detects data transmitted from a particular transmitter by detecting the frequency or wavelength modulation characteristic of the transmitter mask 28 and rejecting signals having different characteristic frequency modulation patterns. Light received from the optical fiber network 42 is coupled into two different receiving channels by coupler 44. The first receiver channel includes a spatial light modulator 46 identical to the spatial light modulator 16 and the second receiver channel includes a spatial light modulator 48 of similar construction to the transmitter's spatial light modulator 16, but having a mask the "opposite" of the transmitter mask 28. Each of the spatial light modulators 46, 48 performs a filtering function on the received optical signals and each passes the filtered light out to an associated photodetector 50, 52. Photodetectors 50, 52 detect the filtered light signals and provide output signals to a differential amplifier 54. The output of the differential amplifier is provided to a low pass filter 56 and the originally transmitted data 58 are retrieved.

FIG. 2 provides an illustration of the receiver circuitry in greater detail. In this illustration, spatial light modulators 46 and 48 are generally similar to the spatial light modulator 16 shown in FIG. 1 and so individual components of the systems are not separately described. Received light 60 is input to the receiver and is split using coupler 62, with a portion of the light directed into spatial light modulator 46 and another portion of the light directed into the other spatial light modulator 48 using mirror 64. Spatial light modulator 46 filters the received light 60 using the same spatial (frequency, wavelength) modulation function as is used in the transmitter's spatial light modulator 16 and provides the filtered light to photodetector 50. Spatial light modulator 48 filters the received light using a complementary spatial filtering function and provides the output to the detector 52. Amplifier 54 provides subtracts the output signals from the two photodetectors. To effect the same filtering function as the transmitter's spatial light modulator 16, the spatial light modulator 46 includes a mask 66 identical to the transmitter mask 28. Spatial light modulator 48 includes a mask 68 that performs a filtering function complementary to masks 28 and 66 so that spatial light modulator 48 performs a filtering function complementary to the filtering function of spatial light modulators 16, 46. In the Kavehrad article, each of these masks 16, 66, 68 is a liquid crystal element so that the masks are fully programmable.

The particular codes embodied in the masks must be appropriate to the proposed optical application. Although CDMA has been widely used in radio frequency (RF) domain communication systems, its application in frequency (wavelength) domain encoding in optical systems has been limited. This is because the success of the RF CDMA system depends crucially on the use of well-designed bipolar code sequences (*i.e.*, sequences of +1 and -1 values) having good correlation properties. Such codes include *M*-sequences, Gold sequences, Kassami sequences and orthogonal Walsh codes. These bipolar codes can be used in the RF domain because the electromagnetic signals contain phase information that can be detected. RF CDMA techniques are not readily applicable to optical systems in which an incoherent light source and direct detection (*i.e.*, square-law detection of the intensity using photodetectors) are employed, because such optical systems cannot detect phase information. Code sequences defining negative symbol values cannot be used in such optical systems. As a result, only unipolar codes, *i.e.*, code sequences of 0 and 1 values, can be used for CDMA in a direct-detection optical system.

The Kavehrad article suggests the adaption of various bipolar codes for the masks within the system illustrated in FIGS. 1 & 2, including masks provided with a unipolar (only 0's and 1's) *M*-sequence or a unipolar form of a Hadamard code. For these sorts of bipolar code, the Kavehrad article indicates that the bipolar code of length N must be converted into a unipolar code sequence of length 2N and that a system including such codes could support a total of N-1 users. The Kavehrad article addresses only a theoretical application of a CDMA system, with little discussion of the implementation of such a system.

A more practical example of an optical CDMA system including a converted bipolar code sequence has been proposed for transmission and detection of bipolar code sequences in a unipolar system. This system is described in a series of papers by L. Nguyen, B. Aazhang and J.F. Young, including "Optical CDMA with Spectral Encoding and Bipolar Codes," Proc. 29th Annual Conf. Information Sciences and Systems (Johns Hopkins University, March 22-24, 1995), and "All-Optical CDMA with Bipolar Codes", Elec. Lett., 16th March 1995, Vol. 3, No. 6, pp. 469-470. This work is also summarized in U.S. Patent No. 5,760,941 to Young, et al., and this work is collectively referenced herein as the Young patent. In this system, schematically illustrated in FIG. 3, the transmitter 80 employs a broad spectrum light source 82 which is split by a beam splitter 84 into two beams 86 and 88 to be processed by two spatial light modulators 90 and 92. The first spatial light modulator 90 comprises a dispersion grating 94 to spectrally disperse the light beam 86 and a lens 96 to direct the dispersed light onto a first spatial encoding mask 98 which selectively passes or blocks the spectral components of the light beam. Lens 100 collects the spectral components of the spatially modulated light

beam and recombination grating 102 recombines the spread beam into encoded beam 104. The "pass" and "block" state of the encoding masks represent a sequence of 0's and 1's, *i.e.*, a binary, unipolar code. The code 106 for the first mask 98 has a code U⊗U*, where U is a unipolar code of length N, U* is its complement and "⊗" denotes the concatenation of the two codes. The second encoder 92 (details not shown) is similar in structure to the first encoder 90 except that its encoding mask has a code U*⊗U. Symbol source 108 outputs a sequence of pulses representing 0's and 1's into a first ON/OFF modulator 110 and through an inverter 112 into a second ON/OFF modulator 114. The two modulators 110 and 114 modulate the two spatially modulated beams of light and the two beams are combined using a beam splitter 116 to combine the two encoded light beams 118 and 120. The modulated light beams are alternately coupled to the output port depending on whether the bit from the source is 0 or 1.

This system can then use a receiver with differential detection of two complementary channels, as illustrated in the receiver of FIG. 2. The receiving channels are equipped with masks bearing the codes U*⊗U and U⊗U*, respectively, and sequences of 0's and 1's are detected according to which channel receives a signal correlated to that channel's mask. The system proposed in the Young patent allows the use of the bipolar codes developed for RF CDMA technologies to be used in optical CDMA systems. However, for a mask of length 2N, only N codes can be defined since the code U and its complement U* must be concatenated on the mask.

Therefore, it is an object of the invention to provide a frequency-domain CDMA encoding/decoding scheme and an optical communication system incorporating such a scheme where the number of users is maximized without raising interference unduly. It is another object of the invention to provide a system providing a relatively simple system for encoding and decoding the light but efficiently using the entire spectrum available.

The throughput of an optical fiber based communication system is defined as the product of each user's data rate times the number of user pairs. The throughput of an optical fiber communication system is a function of the optical source power of the users, the optical source bandwidth, user data rate, the number of users and the desired bit error rate (BER). In many such systems, the limiting factor is the user-to-user interference, which is independent of the optical source power. Such interference imposes a maximum data rate at which the users may transmit information. It is an object of the present invention to increase the system throughput of spread spectrum CDMA communications systems.

Summary of the Preferred Embodiments

These and other objects are obtained by using a spatial encoder with binary or analog

encoding and a decoding receiver or decoder. In particular, a broad-spectrum light source is modulated with data to be transmitted. The modulated light beam is then spatially dispersed, for example using a diffraction grating, and passed through a spatial spectrum-coding mask. The spatial coding mask preferably embodies a unipolar code belonging to a set of unipolar codes that are preferably derived from a set of balanced bipolar orthogonal codes. The dispersed frequencies of the encoded modulated light beam are then recombined to provide a modulated, encoded spread spectrum optical signal for injection into an optical fiber or another optical communication system.

Recovery of the transmitted signal is through the use of a special filter matched to the encoding mask or code. At any receiver, a beam separator, which is in some particularly preferred embodiments a polarization insensitive splitter, diverts part of the beam in the fiber through a diffraction grating to spatially separate the spectrum of the light in the fiber. The spatially spread signal, potentially comprising of many distinct spread spectrum optical communication channels, is passed to a receiver providing signal recovery. Most preferably, the optical signal is converted to an electrical signal by differential detection, the resulting electrical signal is preferably low pass filtered and then, in particularly advantageous embodiments, the electrical signal is provided to a limiting element that removes the negative components of the electrical signal. The differential detection of the receiver can be implemented in a number of ways.

In one embodiment, the masks in the encoder and decoder include unipolar binary codes comprising 0's and 1's such as Walsh codes. The spatially spread light will pass through two decoding masks. One decoding mask is the same as the encoder mask while the other decoding mask is the bit-wise complement of the encoder mask, or otherwise the complement of the encoder mask if the code is, for example, analog. The spatially spread decoded light signals are combined, and the two channels of optical signals are preferably converted to electrical signals by differential detection. Within the illustrative embodiments described here, it is possible to provide an L position mask to define L-1 communication channels for a total of L-1 users.

In another embodiment, the spatially spread light can be detected by an array of detectors. Each detector in the array measures the light power of the corresponding optically spread wave length and outputs a corresponding array of electrical signals. The array of electrical signals will then be processed by a digital signal processor (DSP). The digital signal processing includes multiplying the signal from each detector in the array by a positive or negative one depending on whether the encoder mask bit is a one (transparent) or a zero (opaque). The resulted bit products are then summed before thresholding for data recovery.

This digital processing corresponds to multiplying the signal from individual detectors in the array by the corresponding bit in a Hadamard code, which is the bipolar version of the Walsh encoder code.

To provide a many user system, some embodiments of the present invention provide plural broad band light sources. A particularly desirable and particularly economical implementation of multiple sources having desirable spectral similarities is to provide a single originating light source that is coupled to a fiber, where the output of the source is split, amplified. Each of the split and amplified sources is then split and amplified again, and this process is repeated a sufficient number of times to provide a sufficient number of sources for the many user system. Particularly preferred embodiments decorrelate the different sources, whether generated in this manner or in another that provides at least somewhat correlated sources, by providing delays of different duration along the optical paths between the sources and the corresponding encoders of the system. This might be accomplished by coupling the output of the various light sources through different lengths of optical fiber as delay lines.

Another method of reducing interference, and one that has been observed to be particularly effective, is the use of a data modulation scheme that limits the amount of time that the source is maintained in an on state. Sources may be directly modulated or may be modulated by passing the source light through an element that can modulate the source. In preferred embodiments of the present invention, modulation is accomplished so that a light pulse of predetermined intensity is provided to the optical system when one binary value is to be transmitted and no light is provided to the optical system when the other binary value is to be transmitted. There is typically a clock rate for the data transmission and binary transmissions are typically characterized by a duty cycle. In particularly preferred embodiments of the present invention, it is preferred that the duty cycle be reduced to a low but still detectable level, generally using a duty cycle of less than 50%.

Brief Description of the Drawings

FIG. 1 illustrates a conventional optical fiber mediated CDMA communication system.

FIG. 2 provides a more detailed view of one receiver configuration that might be used in the system of FIG. 1.

FIG. 3 illustrates an encoder for using bipolar codes in an optical CDMA system.

FIGS. 4 & 5 present different configurations of an optical fiber network according to the present invention.

FIG. 6 is a block diagram of a first embodiment of an encoder according to the present invention.

FIG. 7 is a block diagram of a first embodiment of a decoder according to the present invention.

FIG. 8 is a block diagram of a second embodiment of a decoder according to the present invention.

FIG. 9 is a sketch of a liquid crystal mask for use in a third embodiment of an encoder according to the present invention.

FIGS. 10A, B and C are continuous representations of discrete transparency functions for the mask of FIG. 9.

FIG. 11 is a graphical representation of a Fourier transform of light received from the fiber.

FIGS. 12A and B schematically illustrate an encoder and a decoder according to a third embodiment of the invention.

FIGS. 13A, B and C present a graphical representation of a mask and mask functions according to a third embodiment of the invention.

FIG. 14 schematically illustrates an apparatus for generating an array of N broad-spectrum optical sources having sufficient intensity to generate light beams for N channels of communication over a fiber using methods in accordance with the present invention.

FIG. 15 schematically illustrates a polarization insensitive beam separator that is preferred in accordance with preferred embodiments of the present invention.

FIG. 16 illustrates in greater detail the optical detection circuitry schematically illustrated in FIG. 7.

FIG. 17 illustrates a modification to the source generation mechanism of FIG. 14.

FIG. 18 illustrates a set of data streams (a)-(c) that might be used to modulate a source in accordance with aspects of the present invention.

FIG. 19 illustrates a circuit that may be used to generate a pulse stream such as that illustrated in FIG. 18(b) or 18(c) from a data stream such as that illustrated in FIG. 18(a).

Related Applications

The following applications are related to the present application and are each incorporated by reference in their entirety into this application:

"High Capacity Spread Spectrum Optical Communications System," application Serial No. 08/752,211, filed November 19, 1996.

"Optical CDMA System,"application Serial No. 09/126,310, filed July 30, 1998.

"Optical CDMA System Using Sub-Band Coding," application serial no. 09/126,217, filed July 30, 1998.

Detailed Description of the Preferred Embodiments

Particularly preferred embodiments of the present invention provide an optical fiber communications system using spread spectrum code division multiple access techniques to achieve better bandwidth utilization. The particular codes used in the most preferred embodiments of the present invention utilize one or more techniques for decorrelating noise signals or other reducing the interference between different users. Different techniques might be used to accomplish this result, with such techniques being used either individually in or combination with each other. Certain particularly preferred embodiments of the present invention use more than one of the techniques described herein in combination because certain of the techniques are sufficiently independent as to provide additive benefits. These particularly preferred embodiments of the present invention allows greater numbers of simultaneous users to have access to a single optical fiber link, greatly increasing the effective utilization of this resource.

As will be described in greater detail below, it is desirable in many implementations of aspects of the present invention to provide many very similar optical sources. For example, it is desirable to provide at least 128 light sources that are essentially identical in their extent and intensity distribution. Presently envisioned systems require many additional sources. A particularly desirable and particularly economical implementation of multiple sources having desirable spectral similarities is to provide a single originating light source that is coupled to a fiber, where the output of the source is split, for example into four components by a star splitter. Each of the split off components are then amplified to an appropriate level and then each of the split off and amplified components is provided to a separate start splitter. A hierarchical structure of an original source that is split and amplified, with each successive source channel being split and amplified, can be used to develop a great many sources having essentially identical spectral characteristics.

A difficulty observed by the present inventors when implementing this source strategy

is an undesired level of temporal correlation between the different sources. This level of correlation can give rise to undesirable levels of correlation between the different communication channels associated with the different sources. Consequently, preferred embodiments decorrelate the different sources. This might be accomplished by inserting different optical delays along each of the output paths of the different source channels. Such optical delays could consist of optical delay lines. Causing each of the sources to pass through different lengths of fiber delay lines might provide appropriate delays. Delays might alternately be generated using free space propagation through different optical paths. Fiber delays are preferred since they can be implemented using only minimal space, so that the overall optical system can be provided in a sufficiently small space as to allow a wider range of implementations for systems embodying this aspect of the present invention.

Another method of reducing interference, and one that has been observed to be particularly effective, is the use of a data modulation scheme that limits the amount of time that the source is maintained in an on state. Time domain modulated data are provided to the optical communication system by modulating the sources. Sources may be directly modulated or may be modulated by passing the source light through an element that can modulate the source. In preferred embodiments of the present invention, modulation is accomplished so that a light pulse of predetermined intensity is provided to the optical system when one binary value is to be transmitted and no light is provided to the optical system when the other binary value is to be transmitted. There is typically a clock rate for modulated binary data and these binary data streams are typically characterized by a duty cycle. Conventionally, each clock cycle defines a data period and the data can consume some or all of the clock cycle. If all of the clock cycle is consumed by the data, then the duty cycle is said to be 100%. If the data consumes only half of the clock cycle, then the duty cycle is said to be 50%.

In particularly preferred embodiments of the present invention, it is preferred that the duty cycle be reduced to a low but still detectable level, generally using a duty cycle of less than 50%. This has the effect of reducing the total optical signal that is present within the optical fiber system at any point in time. In other words, the use of shortened duty cycles reduces the amount of light within the system, thereby reducing the noise signals and the amount of interference experienced by a desired signal. Circuitry exists for reducing duty cycles considerably. As a practical matter, however, the reduction in duty cycle must be limited in extent so that the optical signal remains detectable.

It is possible to also achieve reductions in interference within the signal detection circuitry of the decoders or receivers. Signals within the two channels of a receiver are preferably detected in a differential fashion, for example by coupling the light from each

channel to different ones of a pair of photodiodes in a back-to-back configuration. The electrical output from the photodiodes will then be a difference measurement of the signal received in the two channels. In particularly preferred embodiments of the present invention, the electrical output signal is low pass filtered and then provided to an electrical square law circuit element such as a diode. This square law element or limiter preferably removes the negative going portions of the received electrical signal and might also be used to amplify the positive going portions of the received electrical signal. The negative going portions of the electrical signal are immediately identifiable as noise and so can be removed to improve the signal to noise ratio of the overall system.

The CDMA encoding/decoding scheme according to the present invention may be applied in optical communication systems such as telecommunications systems, cable television systems, local area networks (LANs), as fiber backbone links within communication networks, and other high bandwidth applications. FIG. 4 illustrates the architecture of an exemplary optical communications system in which the present invention may be applied. A plurality of pairs of users s_{11}, s_{12}, s_{21}, s_{22}, . . . s_{N1}, s_{N2} are connected to an optical fiber medium 130. The first group of users s_{11}, s_{21}, . . . s_{N1} may be proximately located and coupled to the fiber 130 in a star configuration, and the second group of users s_{12}, s_{22}, . . . s_{N2} may be proximately located but remote from the first group and coupled to the fiber 130 in a star configuration. Alternatively, the users in the first group or the second group or both may be coupled to the fiber 130 at separate and distributed points, as shown in FIG. 5. The architecture of FIG. 4 may be more appropriate, for example, for a fiber backbone, whereas the architecture of FIG. 5 may be more appropriate for a telephone system.

Pairs of users s_{j1}, s_{j2} communicate with each other using a channel of the optical fiber, and different pairs of users may simultaneously communicate over the same optical fiber. Each pair of users (s_{j1}, s_{j2}) is assigned a code u_j for transmitting and receiving data between the two users, and different pairs of users are preferably assigned different codes. The transmitting user in a user pair, *e.g.* s_{j1}, encodes the optical signal using the code u_j assigned to the user pair (s_{j1}, s_{j2}), and the receiving user s_{j2} in the pair decodes the optical signal using the same code u_j. This architecture may be used, for example, for a fiber optic backbone of a communication network. The embodiments of the present invention are described as they may be applied in this network environment; other system architectures in which the invention is also applicable are described later.

FIG. 6 shows a first embodiment 140 of a CDMA modulator/encoder. A broadband light source 142, such as a super luminescent diode (SLD) or erbium-doped fiber source (EDFS), is coupled to an optical modulator 144. The optical modulator modulates the light

from the optical source 142 based upon data or other information from the data source 146, using, for example, keying or pulse code modulation. Encoder 150, which is similar to the spatial light modulator 16 shown in FIG. 1 with the exception of the mask and coding scheme, then spatially encodes the modulated broad-spectrum light beam. The encoder 150 includes a diffraction grating 152 that spatially spreads the spectrum of the modulated light beam along an axis. The spatially spread light beam is collimated by a collimating lens 154 and then the collimated beam is passed through the encoding mask 156. The encoding mask, provides a spatially encoded, modulated beam of light that is collected by collimating lens 158 and combined back to a broad spectrum beam by a diffraction grating 160 for injection into the fiber 162, which may be a single mode optical fiber. An optical coupler 164 such as a star coupler, a Y coupler or the like is used to couple the encoded beam into the fiber 162. Alternatively, the light beam may be first encoded with the encoder 150 and then modulated by the modulator 144.

FIG. 7 shows a compatible decoder, which has two channels 170 and 172. Light signals containing a potential plurality of spread spectrum signals are diverted from the fiber 162 using an optical coupler (not shown), and split into two beams through a beam separator 174. The beam separator is most preferably a polarization insensitive element like that illustrated in FIG. 15 and discussed below with reference to that figure. One incoming beam is spread spatially along an axis by a diffraction grating 176 and is then collimated by a collimating lens 180 before being passed through a detection or decoding mask 184. The decoding mask 184 is, in this illustrated preferred embodiment, identical to the encoding mask 156. Light passed through the decoding mask 184 is passed through a collimating lens 188 and a diffraction grating 192 recombines the spatially spread light into a broad spectrum beam. In the other channel, the second component of the split, received beam is spread spatially by a diffraction grating 178 and is then collimated by a collimating lens 182 before being passed through a second decoding mask 186. Most preferably, in this converted-binary Hadamard code, unipolar embodiment of the decoder, this second decoding mask 188 is the bit-wise complement of the encoder mask 184. The beam, after being passed through the second decoding mask 186, is passed through the collimating lens 190 and a diffraction grating 194 to remove the spatial spreading. The output of the first decoder channel 170 may then be supplied to a photodetector 196 to convert the light into an electrical signal. Similarly, the output from decoder channel 172 is supplied to a photo detector 198 to convert the light into an electrical signal. The two electrical signals are then subtracted by the back-to-back arrangement of the two detector diodes, 196 and 198 for being supplied to data and clock recovery hardware and/or software 200. The two electrical signals may also be separately

processed by two gain control circuits, respectively, to adjust for different losses in the two detector channels 170 and 172, before a difference calculation is performed. The differential electrical signal is then detected for data recovery. Data recovery for digital data streams may include, for example, integrating and square-law detecting the difference signal. Data recovery for analog signals provided by analog code mask embodiments of the invention may include, for example, low-pass filtering the difference signal.

FIG. 8 shows another embodiment of the decoder 210. In this embodiment, the beam of light received from the fiber is not split into two channels with two masks, but is instead spread by the grating 212 and is collimated by a lens 214. The collimated light is then intercepted by an array of detectors 216. The number of detectors in the array is equal to the number of bits in the encoder mask. Each detector position corresponds to the encoder mask bit position. The detector signal from each detector in the array is multiplied by either "1" or "-1" depending on whether the corresponding encoder mask bit is a "transparent" or "opaque." The results of all the multiplier outputs are then summed. The sum is then compared with a threshold 218 for data recovery. This digital processing can be performed in discrete logic hardware or in a DSP 220 using software. When an analog mask is used for encoding, the outputs of the detectors may also be multiplied by numbers other than "1" or "-1". It should be noted that in both embodiments of FIGS. 6 and 7 only one encoder mask is used for transmitting data and no concatenated code is required in contrast with prior art designs.

The preferred encoding and decoding scheme according to the present invention is explained next. As used in this specification, "unipolar codes" means code sequences comprising 1's and 0's in the case of binary codes, or code functions having values between 0 and 1 in the case of analog codes. "Bipolar codes" means code sequences comprising -1's and 1's in the case of binary codes, or code functions having values between -1 and 1 in the case of analog codes. A complement of a unipolar binary code u is (1-u), i.e. its bit-wise complement in which 0's are substituted by 1's and 1's are substituted by 0's. A complement of a unipolar analog code f is (1-f). Unipolar binary codes are used as an example in the following description.

In a CDMA system, the basic requirement for a spectral encoding/decoding scheme is that the decoding apparatus at a receiving user be able to recover data signals from the corresponding transmitting user while reducing or eliminating interference from signals from all other users. For some systems, the receiving masks will be fixed as a particular receiver always receives the same channel of data. For other systems, the receiving masks will be programmable so that different signal sources can be selected from the many possible sources. In a spread spectrum CDMA system using an incoherent light source, because an incoherent

optical system can only transmit positive signals (light intensities), and no phase information is available, only unipolar codes may be used for encoding. A unipolar binary code may be represented by a sequence of binary digits, such as u_i=110011110101011, where subscript i designates the i^{th} user pair (or channel). The number of digits in the sequence, N, is referred to as the length of the code. In practice, for the particularly preferred binary unipolar code mask, each of the code values corresponds to a fixed interval slot, either transparent or opaque, on the spatially patterned mask that in turn corresponds to a fixed frequency or wavelength interval in the spatially modulated broad spectrum beam of light.

When a single mask is used for encoding and decoding, the codes are preferably chosen such that they are orthogonal, or:

$$u_i \bullet u_j = \begin{cases} M & \text{if } i=j \\ 0 & \text{if } i \neq j \end{cases} \qquad (1)$$

where "●" denotes the bit-wise dot product of two codes, and M is a constant. When orthogonal codes are used, each transmitting user may transmit signals using a single encoding mask, and the corresponding receiving user may use a single decoding mask identical to the encoding mask to recover the signal from the corresponding transmitting user while rejecting interfering signals from all other users. This desirable outcome, however, occurs only when the codes are chosen to as the binary basis vectors:

$$\begin{aligned} u_1 &= 000......001 \\ u_2 &= 000......010 \\ u_N &= 1\bar{0}0......000 \end{aligned}$$

This set of codes is undesirable in that, since only one digit of the entire code is 1, only one frequency bin of mask passes power through it while the great majority of the bins are blocked. Such a system can be viewed as an incoherent wave division multiple access (WDMA) system. Such codes are undesirable as only about 1/N of the source power is transmitted and the rest of it is wasted.

In the encoding and decoding system described in FIGS. 6 and 7, in which a single mask is used for encoding and two masks are used for decoding, a set of unipolar codes may

be used such that although a code u_i in the set is not orthogonal to other codes u_j in the set according to the definition of orthogonality set forth above. Rather, the code u_i is selected to be orthogonal to the difference between any other code u_j and its complement u_j*, *i.e.*

(2) $$u_i \bullet (u-u_j*) = \begin{cases} M' & if\ i=j \\ 0 & if\ i \neq j \end{cases}$$

where M' is a constant.

It can be seen that the decoders of embodiments of FIGS. 7 and 8 implement the principle of Eq. (2). In the embodiment of FIG. 7, the received light beam at a user j contains signals from all transmitting users i encoded with codes u_i. The first channel 170 having the mask 56 generates a light beam representing $u_i \bullet u_j$, while the second channel having the complementary mask 172 generates a light beam representing $u_i \bullet u_j^*$, and the differentially arranged detectors 62 and 63 generates the difference signal $u_i \bullet (u_j - u_j^*)$. In the embodiment of Fig. 8, the array of detectors 73 outputs signals representing u_i, and the DSP 74 calculates $u_i \bullet (u_j - u_j^*)$ based on the outputs of the detector array 73. According to Eq. (2), the difference signal $u_i \bullet (u_j - u_j^*)$ is non-zero only for the signal from the user that uses a mask having a code u_i. Consequently, such decoders are able to recover the signals from the transmitting user i and reject signals from all other users.

A set of unipolar code that satisfy Eq. (2) may be derived from a set of balanced bipolar binary orthogonal codes v_i that satisfy the following conditions:

(3)

$$v_i \bullet v_j = \begin{cases} M'' & if\ i=j \\ 0 & if\ i \neq j \end{cases}$$

and

(4)

$$v_i \bullet 1 = 0$$

where "1" represents a code in which every digit is 1. The unipolar codes u_i are derived from the bipolar codes v_i by substituting the -1's in v_i with 0's, or

(5)

$$u_i = \frac{1}{2}(v_i + 1)$$

The bipolar code v_i is "balanced" in that they have equal numbers of 1's and -1's (eq. (4)). These particularly preferred unipolar codes u_i thus have equal numbers of 1's and 0's. As a result, half of the light power may be transmitted as signals, thereby promoting the efficient utilization of the source power.

An example of balanced bipolar orthogonal code set is a code set based on Hadamard matrices. A Hadamard matrix is a square matrix the elements of which are 1's or -1's such that all rows are orthogonal to each other and all columns are orthogonal to each other. For example, a 4x4 Hadamard matrix may be:

$$H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

The column (or row) vectors except the first column (or row) of a Hadamard matrix provide a set of balanced bipolar binary orthogonal codes satisfying Eqs. (3) and (4). Thus, a set of unipolar codes $u_1, u_2, \ldots, u_n$ used in the uni-bipolar spread spectrum CDMA system preferred in accordance with the present invention may be constructed by first constructing a Hadamard matrix of size n+1 or greater. Except the first column (or row), every column (or row) of this Hadamard matrix may be used to generate a unipolar code u_j by replacing all -1's with 0's.

For example, for a three-user system, the above 4×4 Hadamard matrix may be used to generate the following codes:

$$\begin{aligned} u_1 &= [1 \quad 0 \quad 1 \quad 0] \\ u_2 &= [1 \quad 1 \quad 0 \quad 0] \\ u_3 &= [1 \quad 0 \quad 0 \quad 1] \end{aligned}$$

Although rules for constructing a general Hadamard matrices of arbitrary size do not exist, there are known methods for constructing Hadamard matrices of certain sizes. For example, Hadamard matrices having a size N that is a power of 2 may be constructed from H_2

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

using a recursive algorithm

$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & -H_n \end{bmatrix}$$

Rules for constructing matrices having a size N that is a factor of 4 are also known.

Although Eqs. (3) and (4) indicate that the bipolar code set used to generate the unipolar codes should be orthogonal and balanced, in practice, it may be acceptable although not desired to use code sets that are "near orthogonal" or "near balanced." A code set is near orthogonal when, for example, $u_i \bullet u_j$ $(i \neq j)$ is substantially smaller than $u_i \bullet u_i$. The codes are near balanced when, for example, $u_i \bullet 1$ is substantially smaller than N. For example, when the length N of the codes is large, changing a few digits of some codes in the set may result in a near orthogonal or near balanced code set. When the codes are not perfectly orthogonal or balanced but only near orthogonal or near balanced, interference from other users may increase and the system performance may deteriorate, but such deterioration may be acceptable so long as the overall system performance is acceptable. Thus, such near orthogonal or near balanced codes may be considered orthogonal or balanced for the purposes of the present invention and are within the scope thereof.

The coding masks 156, 184, 186 in FIGS. 6 and 7 may be either transmissive or reflective. As a practical matter, however, the present inventors have observed that reflective masks are harder to make and do not usually have a desirably large extinction ratio. In some embodiments, the masks are made of liquid crystal material as shown in FIG. 9 divided into a plurality of cells "a" through "L", with L an arbitrary integer and being the maximum permitted length of the code. Such LCD masks are commercially available or are readily made using known technology. The cells form a one-dimensional array arranged along the axis 230

of spatial spectrum spreading caused by the diffraction grating 152. In one embodiment, the control of the cells is analog, meaning that the opacity of each cell is either infinitely adjustable or is adjustable in at least three or more separately controllable stages. Preferably a large number of finite stages, preferably sixty-four or greater levels of opacity should be used. In another embodiment, the control is binary, and Walsh codes (unipolar Hadamard) are used. These masks can be implemented by LCD pixel arrays or by a photonic integrated circuit such as a solid state amplifier array. Alternately, and presently preferred for systems where multiplexing of signals onto a fiber is most desirable, the masks may be fixed and formed on glass blanks. Such fixed masks are most preferably binary masks embodying unipolar Hademard codes. For a reflective mask, the glass may be BK7 or quartz and the reflective regions could be gold. For the presently most preferred fixed, binary, transmission mask, the glass may still be BK7 or quartz and the blocking regions could be chrome. Generally masks are on the order of one to two inches across so that readily available technology can be used to define a mask having 128 different, equal sized and contiguous positions on the mask, as is presently contemplated for an OC-12 application of the present invention. Masks with finer granularity with 256 or 512 positions are readily defined using available technology.

A preferred form of analog coding uses a set of unipolar wavelet functions *fi* derived from balanced bipolar orthogonal wavelet functions g_i using $f_i=(g_i+1)/2$. Eqs. (2) - (4), which are illustrated in the context of binary codes, apply equally to analog codes. In other words, if the bipolar wavelet functions satisfy Eqs. (3) and (4), then the derived unipolar wavelet functions satisfy Eq. (2). In one embodiment, the wavelet functions are discrete harmonic spatial sine waves (represented for purposes of illustration as continuous functions) as shown in FIG. 5. The ordinate axis is the axis along which the frequencies of the beam are spread and the abscissa is the relative transparency of the beam passing through a cell. In particular, a first encoder mask transparency function shown in FIG. 10A may have a spatial frequency of 1/L, where L is the number of cells. The mask of that first encoder is a discrete (as opposed to continuous) cosine wave in terms of transparency having one cycle over the frequency spectrum of L, such that the lowest and highest frequency portion of the encoded spectrum have the maximum intensity and the mid-range spectral frequencies have the lowest intensity. A second encoder mask may for example have a spatial frequency intensity mask of twice the frequency of the first encoder with two full cycles across the length of the encoder L of FIG. 10B. Still further a third encoder may have a frequency three times the frequency of the first encoder as shown in FIG. 10C. Other higher harmonics are preferably used, and preferably to maximize the system throughput, the maximum number of codes should be over one hundred and preferably over several hundred for higher usage systems.

The maximum number of harmonics or Walsh code bits (and therefore, the maximum number of codes) is limited only by the number of cells in the mask. For the analog mask, the number of different levels of opacity permitted in the mask, results in the quantization noise in the encoder. Alternatively, rather than using cosine waves, Chebyshev polynomials could also be used as they are orthogonal with respect to each other.

Using cosine waves for the encoding function also permits an easier decoder design. In particular, if one takes the spatial Fourier transform of the received signal, the received signal can be separated through a spatial filter for the frequency of the desired signal and then that signal can be recovered. As a simple example, FIG. 11, shows the Fourier transform of a signal received from a fiber where the separate encoded signals include 1/L, 2/L, 4/L and 8/L. Any one of these signals may be readily obtained by filtering for that particular spatial frequency in the received signal.

In a preferred third embodiment of the disclosed encoder, rather than pulse code modulate the data, an alternative method may be used for modulating signals using two codes as is shown in FIG. 12A. In this embodiment of an encoder 238, the optical path for the spatially spread light source 240 is switched between a first mask 242 and a second mask 244, which is complementary to the first mask 242, by a switcher 246 responsive to data from a data source 248, the first mask encoding the light to provide a digital "one" signal and the second mask encoding the light to provide a digital "zero" signal for the same code channel. The modulator switches the light path between two different encoder masks using one liquid crystal in a manner similar to the binary mask receiver embodiment. The light from both masks is then summed by a summer 250 and then provided to the optical communications channel such as a optical fiber (not shown).

Receiving data proceeds in the converse manner as shown in FIG. 12B. A decoder 260 receives light from the communications channel and generates the spatially spread spectrum of the received light with receiving input optics 262 through masks 264, 266 which are identical to the mask 242 and the mask 244, respectively. The light from the masks 264 and 266 is then provided to a differential receiver 268 in the manner described above in the binary receiver embodiment. The signal from the receiver 268 may then be processed by a digital signal processor 270 for recovery of the data.

FIG. 13A shows one alternative embodiment of the masks appropriate for coding where two different masks are used for transmitting ones and zeros. In a first version, the mask formed of L cells in a liquid crystal mask 280 is divided into four parts, 282, 284, 286 and 288. Parts 282 and 284 comprise L/2 cells each along a first linear array arranged along the axis of spreading of the spectrum on a first row to encode a "one" for this particular code

channel and at a second column, cells 286 and 288 also comprise L/2 cells arranged along the same axis for encoding a "zero" for this same channel. Preferably, the discrete transparency functions for parts 282, 284 are the complements of each other such as shown in FIG. 13B, where the ordinate represents spatial frequency and the abscissa represents intensity. For transmitting the other possibility (i.e. the zero), as shown in FIG. 13C, the complements of the discrete intensity functions for parts 286 and 288 are reversed. In other words, the portion of the mask in section 282 is identical to the portion of the mask in 288 and the portion of the mask in 284 is identical to the portion of the mask in 286.

In addition to having masks where the coding is complementary, it is also possible to provide coding where a first portion 282 of the mask is the orthogonal wave function and the second half is all opaque for a "zero" 284 and the second level, the first half 286 is all opaque and the second half is the same pattern as the first half 282 to make a "one." Alternatively, the first halves 282, 286 can be a first polynomial such as a sine wave and the second halves 284, 288 can be a second polynomial such as a Chebyshev function.

Although specific embodiments of encoders and decoders according to embodiments of the invention are disclosed, other embodiments of the invention are also possible. For example, while discrete wavelet functions are used for encoding, it is possible to have masks that permit continuous functions for coding. For example, the masks may be formed photographically.

The optical systems 150, 170 and 172 in the encoder of FIG. 6 and decoder of FIG. 7 may be generally referred to as optical chambers. An optical chamber, which may be a set of discrete optics or an integrated optical device, spectrally encodes an input broad band optical signal by selectively attenuating the spectral components of the signal according to a "code." The code, which may be binary or analog, determines the degree of attenuation of each spectral components of the input signal. In the illustrated embodiments, the optical chambers are implemented with diffraction gratings, collimating lenses and an optical mask having a code, but other implementations are also possible.

Furthermore, it should also be understood that all of the disclosed embodiments of encoders and decoders could also be applied to analog modulation of the optical signal.

Similarly, while only CDMA techniques have been described above, those of ordinary skill in the field will readily understand that depending upon system parameters, the system may also be used with wavelength (frequency) division multiplexing and time division multiplexing. For example, different coding schemes may be used for different portions of the optical spectrum so that wavelength division multiplexing may be used. In addition, the codes may be shared on a time sharing basis to provide for time division multiplexing. Also, optical

spatial (frequency domain) CDMA can be combined with time-domain optical CDMA to increase the number of codes and the users in the network. In the time domain spread spectrum embodiments, several users are provided with different time domain spread spectrum codes for encoding the data before the data is provided to the optical encoder. However, these users can share the same wavelength encoding schemes discussed above. Of course, at the decoder, once the received optical information is converted back into the electrical digital domain, the digital signal must be processed according to the time domain spread spectrum code to recover the desired transmitted information.

In addition to the various different possible types of combinations of multiplexing schemes that are possible, various network algorithms may also be implemented. For example, the present invention may be applied to various fiber communication system architecture, such as a network environment shown in FIG. 5, in which a plurality of users $s_1, s_2, \ldots s_N$ are connected to an optical fiber medium 130 and each user s_j may communicate with any other user s_i over the optical fiber. Each user or node s_j is assigned a code u_j for receiving data from other users, and different users are preferably assigned different codes. When a user s_i transmits data to a user s_j, the transmitting user s_i encodes the optical signal using the code assigned to the receiving user s_j, and the receiving user decodes the signal using its assigned code. This may require that the transmitting user be able to dynamically vary the code it uses to transmit data depending upon the code of the intended recipient user. The codes for any one node may be assignable from one or more master nodes distributed throughout the network. Hence, when a node in a network comes on line, it requests a code or codes for encoding for selecting one of the possible spread spectrum channels over which to communicate. When that node leaves the network, the code that had been used by that particular node may be reassigned to a different node in the network. Various schemes may be used for making such requests such as CSMA/CD technique or token passing on a permanently assigned channel. Alternatively, token passing techniques may be used for gaining codes for securing one of the code division channels.

In addition, the disclosed embodiments permit an increase in the number of simultaneous users. In particular, in prior art schemes such as those discussed above, the maximum number of simultaneous users that are permitted for the same number of codes is $2^{N/2}$ where N is the maximum number of codes. However, in the disclosed embodiment, the maximum number of codes with holding everything else constant is 2^N. Thus, total system throughput is dramatically increased, thereby permitting a system throughput of at least one half of a terabit, with the total system throughput being determined by the maximum number of simultaneous users, and the users data rate.

A particularly preferred implementation of an overall optical fiber communication system in accordance with the present invention is now described and illustrated. This overall system may be used for adding capacity, *i.e.*, increasing the bandwidth, of an optical communication system that connects plural users of an extended fiber optic connection. FIG. 14 illustrates a preferred apparatus for generating a plurality of broad-spectrum sources in a cost effective manner using a single erbium-doped fiber source and a hierarchy of erbium-doped fiber amplifiers to provide enough channels of sources, each with sufficient intensity for driving a channel of the optical communications system. As shown, a single erbium-doped fiber source 300 outputs light with an acceptably broad spectrum, generally providing a bandwidth of about 28 nanometers in wavelength over which the intensity of the source varies by less than about 5 dB. The 28-nanometer bandwidth corresponds to a system bandwidth of about 3.5 THz. The output of the erbium-doped fiber source, also known as a super luminescent fiber source, is provided over a fiber to a splitter such as a star coupler 302 which splits the input source signal and provides the output over four fibers to an array of four fiber amplifiers 304.

As the output of the fiber source 300 is split into four different sources, the intensity drops in the expected manner. Each of the four split off sources is thus amplified by the four fiber amplifiers to provide four broad-spectrum light beams preferably each having an intensity approximately equal to the original source 300 intensity. For the illustrated 128 channel system, this process is repeated through several further hierarchical stages. Thus, the outputs from the four fiber amplifiers 304 are provided over fibers to a corresponding set of four splitters 306, which may also be star couplers. The splitters 306 split the output from the fiber amplifiers into a plurality of outputs also of reduced intensity. The split off output from the splitters 306 are then provided to a further array of fiber amplifiers 308, which preferably amplify the intensity of the plural channels of broad-spectrum light to provide a next set of source light beams 310 having an appropriate intensity. This process is repeated until a sufficient number of broad-spectrum sources having an appropriate intensity are generated, for example 128 independent sources for the illustrative 128-channel fiber communication system. This hierarchical arrangement is preferred as using a single originating source and a number of fiber amplifiers to obtain the desired set of broad-spectrum light sources, which advantageously takes advantage of the lower price of fiber amplifiers as compared to the fiber source.

After sufficient channels of source light have been generated, the channels of source light are provided to an array of spatial light modulators or encoders like that shown in FIG. 6. The 128 different encoders use a 128-bin mask to spatially encode the input light signal, with

each of the 128 masks presenting a different one of a unipolar Hadamard code vector generated in the manner discussed above. Most preferably, each of the masks is a fixed mask for use in a transmission mode, with the mask having a total of 128 equal sized bins, with the bins spanning the usable width of the linear mask. Thus, the 128 bins span a total of about 3.5 THz (28 nanometers) in bandwidth, with each adjacent bin defining a subsequent frequency interval providing about 25 GHz of bandwidth. Each of the equal sized bins of the fixed mask is assigned according to the code vector to have one or the other of two binary values. One of the two binary values is identified by a blocking chrome stripe on the glass substrate of the mask and the other binary value is identified by an unblocked, transparent stripe on the glass substrate. Each of the 128 channels of the communication system is then defined by a distinct spatial encoding function and each of the channels is also modulated with a time-domain signal, for example using a modulator 144 like that shown in FIG. 6. After the various channels are modulated both spatially (equivalently, frequency) and temporally, the 128 channels are combined and injected into a fiber.

Long distance transmission for this fiber communication system is managed in a manner similar to the manner other conventional fiber communication systems are managed. As is conventional, it is typical to use a single mode fiber. In addition, the signals on the fiber will undergo dispersion and losses. It is preferable that the signals on the fiber be amplified using a conventional fiber doped amplifier at regular intervals, for example, every forty to eighty kilometers.

At the other end of the transmission fiber, the combined light signals are split, amplified, and provided to an array of 128 receivers, each corresponding to one of the fixed mask channels defined by the 128 transmitters coupled into the fiber. The primary purpose of the illustrated embodiment is to expand the usage or loading on the fiber, so the receivers also include fixed masks so that each receiver is dedicated to a single one of the 128 channels. The receivers, which may have the structure shown in FIG. 7, are each dedicated to a particular channel defined by a particular transmitter by including within the receiver one mask identical to the transmitter mask and a second mask that is the bit-wise complement of the transmitter mask. As discussed above, it is possible and in other embodiments desirable to provide either the receiver or the transmitter with a variable mask such as one using a programmable LCD element. For the illustrated embodiment, however, the use of fixed masks on both the transmitting and receiving ends of the communication system provides a reduced cost system that provides significantly improved bandwidth for a high volume fiber link.

As discussed above, recovery of optical signals from the fiber communication link is accomplished using a receiver that separates the light beam received from the optical system

into two components that should have substantially similar power levels. A particularly preferred aspect of the present invention is illustrated in FIG. 15, which shows a beam separator that is preferably used at the input to the receiver. A beam separator in accordance with the present invention is capable of separating the received light beam into two beams of sufficiently equal power levels to allow the preferred differential detection scheme of the optical CDMA receivers to effectively detect a desired user channel.

An embodiment of a polarization insensitive beam separator might consist of a first polarization sensitive element that divides the received light beam into first and second channels of light with each channel having a different one of two orthogonal polarizations. For example, one channel of light might include the vertically polarized component of the received light beam and the other channel might include the horizontally polarized component of the received light beam. The polarization of one of the channels is then converted to the polarization of the other light beam. For linearly polarized light this might consist of rotating the polarization of the light. The two channels of light are then recombined and provided to a beam splitter. This beam splitter is typically a polarization sensitive element that accurately splits the combined beams into two beams of substantially equal power because the polarization of the combined beams is well defined and predictable.

Referring to FIG. 15, a specific embodiment is described in which light is received from a single mode fiber 350. Since the fiber 350 is generally not polarization preserving and the light within the fiber 350 is likely linearly polarized in an arbitrary direction, it is convenient to use a conventional linear polarizer as a beam splitter 352 or polarization analyzer. The polarization sensitive element 352 preferably separates the input light beam into two orthogonal polarization components and provides those two components to two different optical paths 354, 356. Generally different power levels will be present along each path. The illustrated optical paths may propagate through free space or may proceed through polarization preserving fibers. In either case, the polarization of the light within each arm will be of a uniform polarization until the polarization is altered.

One component of the light is provided along optical path 354 and maintains a vertical linear polarization 358 throughout the optical path 354. Along the other optical path 356, the polarization is initially horizontal 360 and then the polarization is rotated by 90° by a rotation element 362 so that the polarization of the second optical path's light becomes linear vertical as indicated at 364 in FIG. 15. When the second optical path 356 propagates through free space, the rotation element may be a ½ waveplate or an appropriate Faraday rotator. When the second optical path 356 propagates through a polarization-preserving fiber, the rotation element 362 is most preferably effected by a mechanical rotation of the fiber by 90°. Most

generally the rotation of the fiber will proceed continuously over a length of the fiber. Of course, it is possible to perform the rotation through other means, such as by inserting a rotation element at an end of the fiber of the second optical path.

Once the two beams on the two optical paths have had their polarizations properly oriented, the two beams are recombined and then split into a pair of substantially equal power beams to propagate along two additional beam paths. After the beams from paths 354 and 356 are combined, it is possible to use a typical polarization sensitive beam splitter 366 to divide the beams into two substantially equal power beams. The two desired output beams are provided along optical paths 368 and 370 preferably through single mode optical fiber with linear polarizations in the illustrated embodiment. Comparing FIG. 7 and FIG. 15, the input fiber 350 of FIG. 15 may correspond to the input fiber 162 of FIG. 7 and the output beams along optical fiber paths 368, 370 (FIG. 15) correspond to the two optical paths shown propagating from element 174 of the FIG. 7 embodiment. The split, received beams are then provided to the filtering elements 170, 172 of FIG. 7 where the two channels are analyzed through the masks shown in FIG. 7.

In the illustrated optical CDMA system, it is very desirable to reduce the interference between different channels of users or of different multiplexed signals so that a greater number of channels can be provided over a single fiber. Various mechanisms have been identified to perform this task and are described in the present application and in the other applications incorporated by reference herein. A fundamental way in which the present system reduces interference is by injecting light into the optical communication system only to indicate one binary state. The source is modulated so that the source produces an output intensity to indicate one logical binary state, for example, a logical 1. No light is provided to indicate a logical 0. This has the effect of reducing the overall interference in the system. Of course, the particularly preferred coding scheme, including the receiving system including different channels with complementary filtering functions, provides a very significant and basic mechanism for reducing interference.

The preferred electrical system, illustrated schematically in FIG. 16, also provides a mechanism for reducing interference. The subsystem illustrated in FIG. 16 provides further detail on the back-to-back diode arrangement indicated at 196, 198 in FIG. 7. The two complementarily filtered optical signals are provided to the back-to-back diodes 196, 198, which effect both a square law optical detection but also a differential amplification function. Other combinations of optical detectors, difference detection and electrical amplification are known and might well be substituted for these functions. In particularly preferred embodiments of the present invention, the electrical output signal 200 from the diode pair 196,

198 and is then low pass filtered by filter 380. The low pass filtering is performed to remove high frequency noise signals. In the illustrated system which might receive one of plural channels video data from the optical communication system at a data rate of approximately 622 MHz, the filtering might pass frequencies of 630-650 MHz. The filtered electrical signal is then provided to an electrical square law circuit element 382 such as a diode. This square law element or limiter preferably removes the negative going portions of the received electrical signal and might also be used to amplify the positive going portions of the received electrical signal. The negative going portions of the electrical signal are immediately identifiable as noise and so can be removed to improve the signal to noise ratio of the overall system. The electrical signal output from the limiter 382 is then analyzed to detect signals above a threshold value, which signals are recognized as transmitted ones.

A particularly desirable and particularly economical implementation of multiple sources having desirable spectral similarities is to provide a single originating light source that is coupled to a fiber, where the output of the source is split, for example into four components by a star splitter. Each of the split off components are then amplified to an appropriate level and then each of the split off and amplified components is provided to a separate start splitter. A hierarchical structure of an original source that is split and amplified, with each successive source channel being split and amplified, can be used to develop a great many sources having essentially identical spectral characteristics.

Another method of reducing interference is to reduce the correlation between different ones of the noise signals. A difficulty observed by the present inventors when implementing the source strategy shown in FIG. 14 is an undesired level of temporal correlation between the different sources. This level of correlation can give rise to undesirable levels of correlation of noise sources or of correlation between the different communication channels associated with the different sources. Consequently, preferred embodiments decorrelate the different sources. This might be accomplished by inserting different optical delays along each of the output paths of the different source channels. One simple mechanism for accomplishing this is illustrated in FIG. 18. A large number of distinct sources 400-403 are defined, for example using the technique illustrated in FIG. 14 and discussed above, so that the sources provide similar optical outputs with similar spectral bandwidths and spectral power distribution. While four sources are shown, the system will typically include 128 or more total sources corresponding to 128 or more users.

The outputs of each of the sources 400-403 are passed through a delay to reduce the temporal correlation between the different sources. Such optical delays could consist of optical delay lines or extended optical propagation paths. Causing each of the sources to pass

through different lengths of fiber delay lines is the most preferred mechanism for providing appropriate delays. Delays might alternately be generated using free space propagation through different optical paths. Fiber delays are preferred since they can be implemented using only minimal space, so that the overall optical system can be provided in a sufficiently small space as to allow a wider range of implementations for systems embodying this aspect of the present invention. Referring once again to FIG. 17, appropriate delays are effected by passing the output of each of the sources 400-403 through different lengths of single mode fibers 404-407. The different length fibers are selected to impose a delay of between about one and about two or more times the data rate on successive sources. Considering a data rate of approximately 622 Mbt/sec, an appropriate delay can be fashioned by adding about one and a half feet of optical fiber (equivalent to ~1.5 GHz) for each desired delay. Thus, for the first source 400, no addition fiber would be added as this represents the baseline. For the second source 401, 1.5 feet of additional fiber 405 would be included in the output path and for the third source 402, a three foot length of fiber 406 beyond the baseline length of fiber 404 is provided. Similarly, the output from source 403 is coupled through a fiber 407 that is about 4.5 feet (~4.5 GHz) longer than fiber 404. Each of the users within a system, which may total 128 users or more or equivalently might total 128 channels of multiplexed data, is provided with a source originating from a central source and delayed by an amount different from all of the other sources. It will of course be appreciated that different mechanisms for achieving optical delays are known and could be practiced to achieve similar results.

Another method of reducing interference, and one that has been observed to be particularly effective, is the use of a data modulation scheme that limits the amount of time that the source is maintained in an on state. Time domain modulated data are provided to the optical communication system by modulating the sources. Sources may be directly modulated or may be modulated by passing the source light through an element that can modulate the source. In preferred embodiments of the present invention, modulation is accomplished so that a light pulse of predetermined intensity is provided to the optical system when one binary value is to be transmitted and no light is provided to the optical system when the other binary value is to be transmitted. A schematic example of the modulation of a source with a data stream is shown in FIG. 6.

In a modulating data stream, there is typically a clock defining a data rate for modulated binary data and these binary data streams are typically characterized by a duty cycle. This is illustrated schematically in FIG. 18, where various data streams (a)-(c) are shown on a background of clock cycle starts identified by the vertical dashed lines. Conventionally, each clock cycle defines a data period and the data can consume some or all of

the clock cycle. If all of the clock cycle is consumed by the data, then the duty cycle is said to be 100%. If the data consumes only half of the clock cycle, then the duty cycle is said to be 50%. This is shown in FIG. 18(a) and consists of an signal that may be "ON" as much as one half of the time. It is desirable to further reduce the amount of time that light is being injected into the system to further reduce the amount of interference that exists between the various users or channels within the system. As such, data modulation is accomplished in particularly preferred embodiments of the present invention using a data stream with a duty cycle of 25% like that shown in FIG. 18(b) or even shorter such as that shown in FIG. 18(c) which has a duty cycle of 12.5%.

In particularly preferred embodiments of the present invention, it is preferred that the duty cycle be reduced to a low but still detectable level, generally using a duty cycle of less than 50%. This has the effect of reducing the total optical signal that is present within the optical fiber system at any point in time. In other words, the use of shortened duty cycles reduces the amount of light within the system, thereby reducing the noise signals and the amount of interference experienced by a desired signal. Circuitry exists for reducing duty cycles considerably. As a practical matter, however, the reduction in duty cycle must be limited in extent so that the optical signal remains detectable. The amplification of the input source or the amplification of the detection scheme must be increased in proportion to the reduction in the data duty cycle. The noise floor associated with the amplifier then establishes the limit on how small the duty cycle might be reduced. The duty cycle cannot be reduced below the level at which amplifier noise comes to dominate the signal.

The data source (146 in FIG. 6) might be selected to provide data streams with the desired duty cycle characteristics. On the other hand, it is typically preferable to provide greater flexibility so that any input data stream, for example the 50% duty cycle stream illustrated in FIG. 18(a), can be converted into a comparatively short duty cycle pulse. FIG. 19 schematically illustrates a device for converting a input data stream like that of FIG. 18(a) into a data stream like that shown in FIGS. 18(b) or 18(c). The circuit of FIG. 19 is placed between the data source 146 and the modulator 144 in FIG. 6. A data stream is input from the data source 146 to the pulse modifier 420 shown in FIG. 19. The electrical signal travels along two paths so that a portion of the signal passes through a delay element 422. Delay element 422 creates a delay with respect to other path's undelayed signal. The two signals are recombined by a recombiner 424 in a manner that produces a positive pulse only while the undelayed and the delayed signals are both "1". The delay circuit 422 may be a programmable delay or it might consist of a series of inverters. The recombiner might, for example, be an exclusive OR gate. By use of the FIG. 19 circuit, pulses of any chosen duty cycle can be

provided.

While the present invention has been described with particular emphasis on certain preferred embodiments of the present invention, the present invention is not limited to the particular embodiments described herein. Those of ordinary skill will appreciate that certain modifications and variations might be made to the particular embodiments of the present invention while remaining within the teachings of the present invention. For example, while the above embodiments have been presented in terms of communications systems mediated over fiber, aspects of the present invention are immediately used in an over the air optical system. As such, the scope of the present invention is to be determined by the following claims.

What is claimed is:

1. An optical communication system, comprising:

a plurality of light sources;

a plurality of data sources providing plural data streams;

a plurality of pulse modifiers;

a plurality of modulators, each of the data sources coupled through a corresponding one of the pulse modifiers and to a corresponding one of the modulators, the pulse modifiers reducing the width of pulses within corresponding ones of the data streams so that the light sources are modulated with the pulse modified data streams; and

a plurality of encoders each receiving an optical output from a corresponding one of the light sources, wherein each of the encoders includes:

a first spectral filtering assembly embodying a first code, the code being a sequence of N digits each having one of at least two values, the optical chamber spectrally encoding an input beam of light with the code by separating the beam of light into N spectral components each corresponding to a digit of the code, attenuating each spectral component according to the value of the corresponding code digit, and recombining the spectral components to generate an output encoded beam of light, wherein the first optical chamber is disposed to spectrally encode the first beam of light.

2. The optical communication system of claim 1, wherein the first code is selected from a set of unipolar codes in which each code in the set is orthogonal to the difference between any other code in the set and the complement of the other code.

3. The optical communication system of claim 1, further including a plurality of decoders coupled to receive signals from an optical fiber and to recover transmitted data from the optical fiber, each of the decoders comprising:

a phase insensitive optical power separator for splitting a portion of the light signal carried by the optical fiber into approximately equal power components.

4. The optical communications system of claim 3, wherein each of the decoders further comprises:

second and third spectral filtering assemblies coupled to receive the first and second components of the received light, the second spectral filtering assembly embodying the first code and the third spectral filtering assembly embodying a complement of the first code, the

second and third spectral filtering assemblies outputting first and second filtered components of the received light; and

an optical detector provided to receive the first and second filtered components of the received light, the optical detector providing an electrical signal output.

5. The optical communication system of claim 4, wherein the electrical signal output represents a differential measurement between the first and second filtered components of the received light.

6. The optical communication system of claim 4, wherein the electrical signal output is provided to a limiting circuit that removes electrical noise signals having a sign opposite of the recovered data.

7. The optical communication system of claim 4, wherein the electrical signal output is provided to a limiting circuit comprising an electrical square law detector.

8. The optical communication system of claim 1, wherein the pulse modifiers include a circuit having a delay path in parallel with an undelayed data path and wherein signals from the delay path and the undelayed path are combined to provide a shortened pulse.

9. The optical communication system of claim 8, wherein the signals from the delay path and the undelayed path are combined with an exclusive OR gate.

10. An optical communication system, comprising:

a plurality of light sources;

a plurality of optical delays, outputs of the plurality of light sources being delayed, with a first light source being delayed by a first amount greater than a delay of a second light source and less then a delay of a third light source;

a plurality of data sources providing plural data streams;

a plurality of modulators, each of the data sources coupled to a corresponding one of the modulators; and

a plurality of encoders each receiving a delayed optical output from a corresponding one of the light sources, wherein each of the encoders includes:

a first spectral filtering assembly embodying a first code, the code being a sequence of N digits each having one of at least two values, the optical chamber

spectrally encoding an input beam of light with the code by separating the beam of light into N spectral components each corresponding to a digit of the code, attenuating each spectral component according to the value of the corresponding code digit, and recombining the spectral components to generate an output encoded beam of light, wherein the first optical chamber is disposed to spectrally encode the first beam of light.

11. The optical communication system of claim 10, further including a plurality of decoders coupled to receive signals from an optical fiber and to recover transmitted data from the optical fiber, each of the decoders comprising:

a phase insensitive optical power separator for splitting a portion of the light signal carried by the optical fiber into approximately equal power components.

12. The optical communication system of claim 2, wherein the phase insensitive optical power separator includes:

a first polarization sensitive element positioned to receive the light signal and to separate the light signal into a first and a second light component, the first light component having a first polarization and the second light component having a second polarization as output from the first polarization sensitive element;

a first beam path along which the first light component travels and a second beam path along which the second light component travels;

a polarization modifier positioned along the second beam path, the polarization modifier changing the polarization of the second light component to be predominantly the first polarization;

a beam splitter receiving the first and second light components and splitting the first and second light components into third and fourth light components.

13. The optical communication system of claim 10, further comprising:

a plurality of pulse modifiers;

a plurality of modulators, each of the data sources coupled through a corresponding one of the pulse modifiers and to a corresponding one of the modulators, the pulse modifiers reducing the width of pulses within corresponding ones of the data streams so that the light sources are modulated with the pulse modified data streams.

14. The optical communications system of claim 13, wherein each of the decoders further comprises:

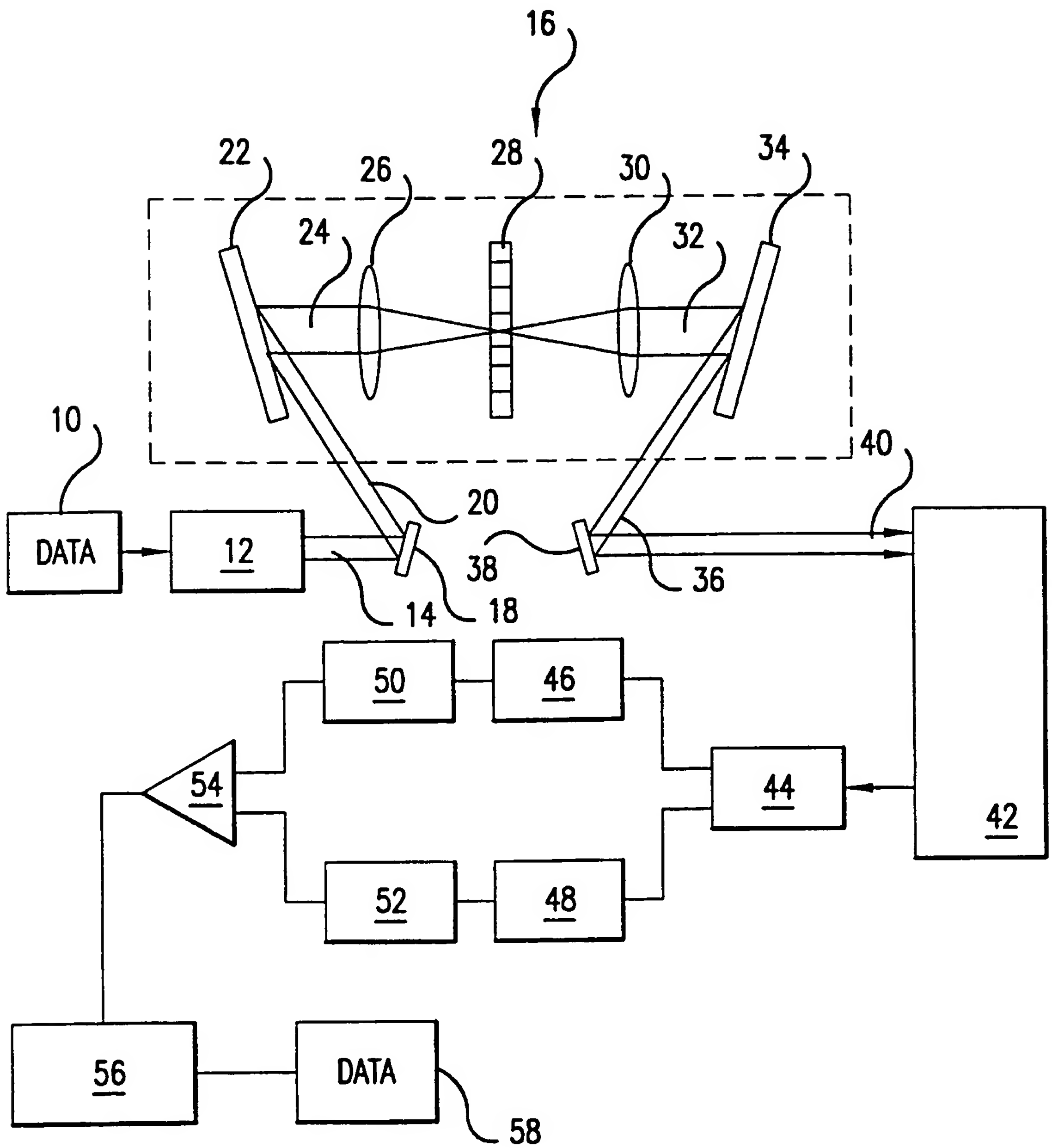
second and third spectral filtering assemblies coupled to receive the first and second components of the received light, the second spectral filtering assembly embodying the first code and the third spectral filtering assembly embodying a complement of the first code, the second and third spectral filtering assemblies outputting first and second filtered components of the received light; and

an optical detector provided to receive the first and second filtered components of the received light, the optical detector providing an electrical signal output.

15. The optical communication system of claim 14, wherein the electrical signal output represents a differential measurement between the first and second filtered components of the received light.

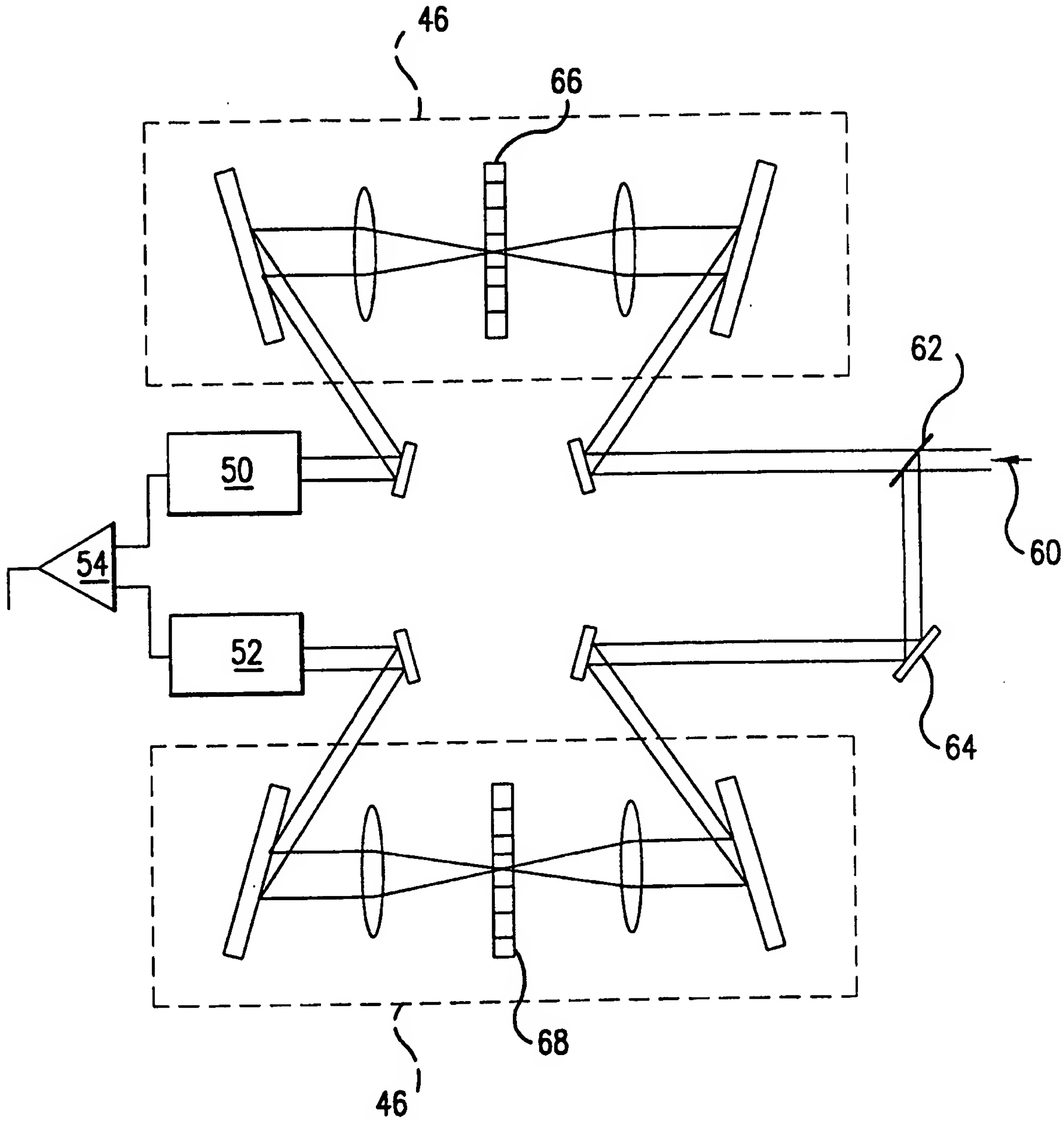
16. The optical communication system of claim 15, wherein the electrical signal output is provided to a limiting circuit that removes electrical noise signals having a sign opposite of the recovered data.

17. The optical communication system of claim 15, wherein the electrical signal output is provided to a limiting circuit comprising an electrical square law detector.



PRIOR ART

FIG. 1



PRIOR ART

FIG. 2

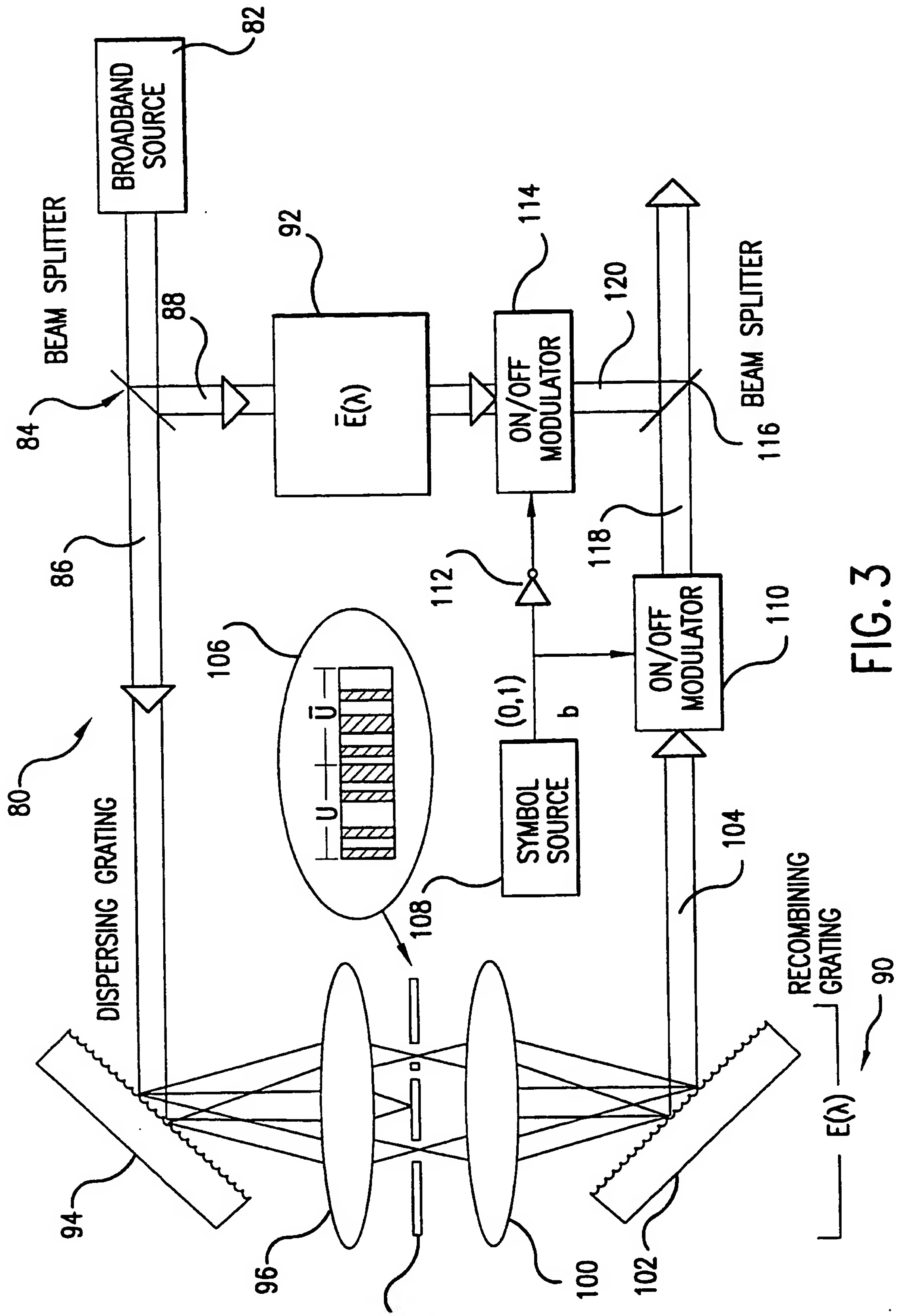

80
82
BROADBAND SOURCE
BEAM SPLITTER
84
86
88
92
$\bar{E}(\lambda)$
ON/OFF MODULATOR
114
120
BEAM SPLITTER
116
118
112
ON/OFF MODULATOR
110
(0,1)
b
SYMBOL SOURCE
108
106
U
$\bar{U}$
DISPERSING GRATING
104
RECOMBINING GRATING
90
E(λ)
94
96
98
100
102

FIG. 3

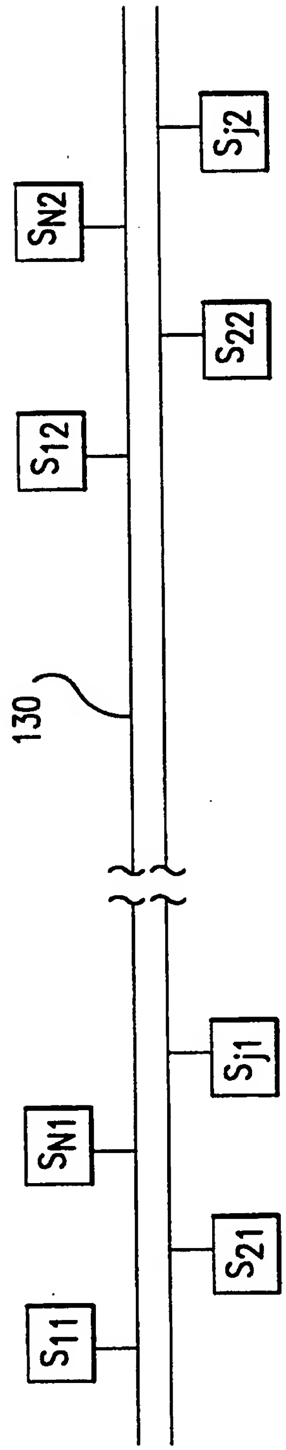


FIG. 4

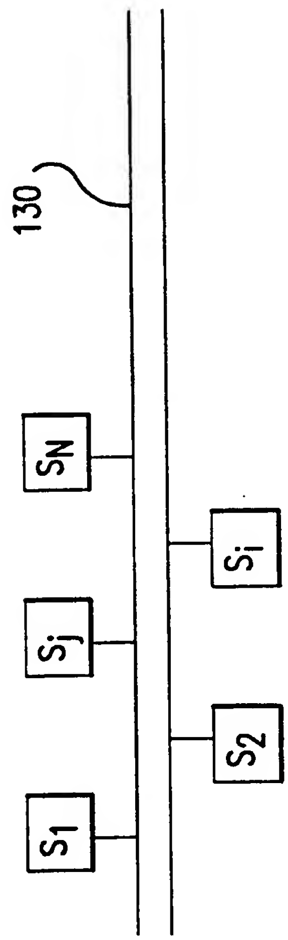


FIG. 5

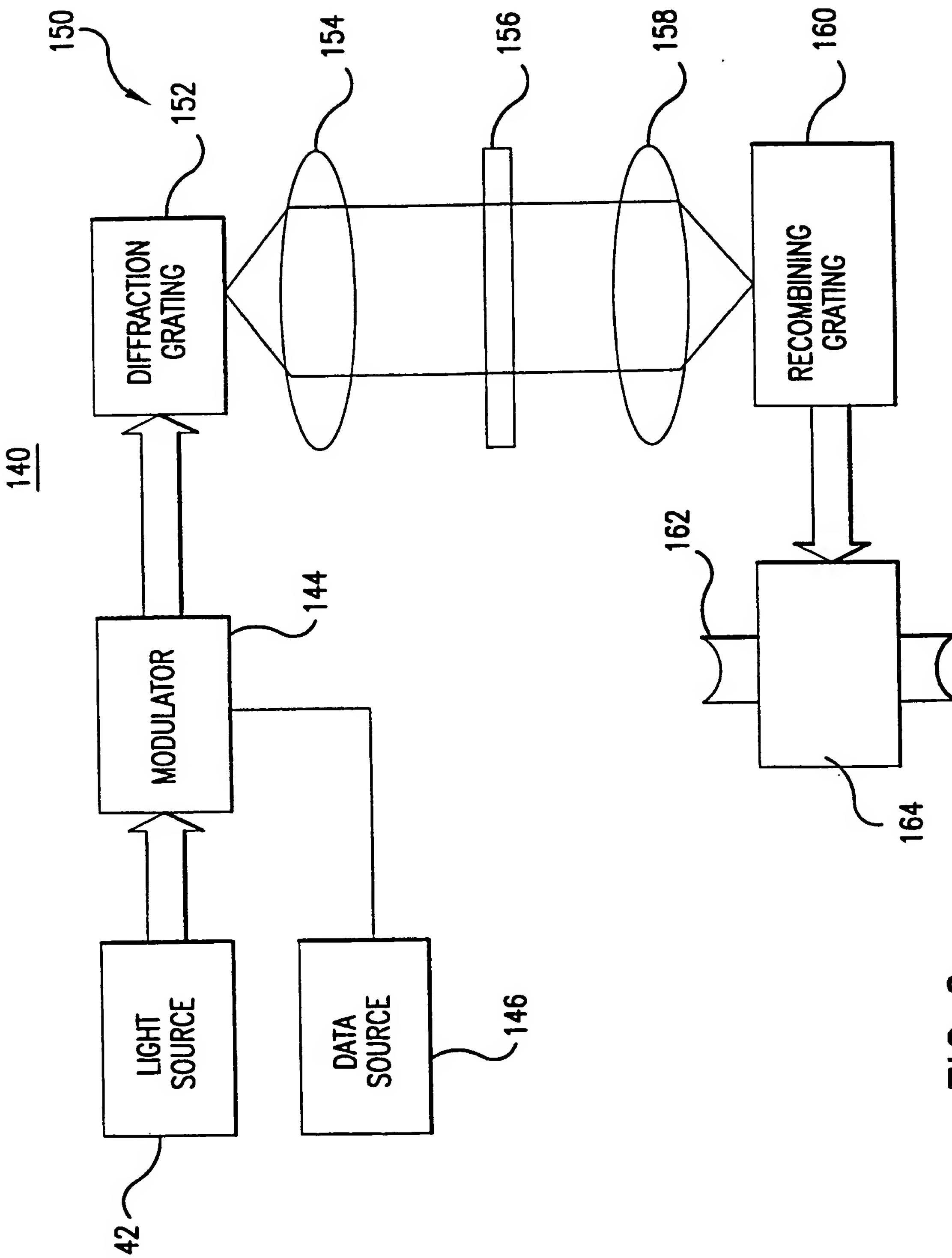

140
150
152
DIFFRACTION GRATING
154
156
158
160
RECOMBINING GRATING
162
164
144
MODULATOR
LIGHT SOURCE
142
DATA SOURCE
146

FIG. 6

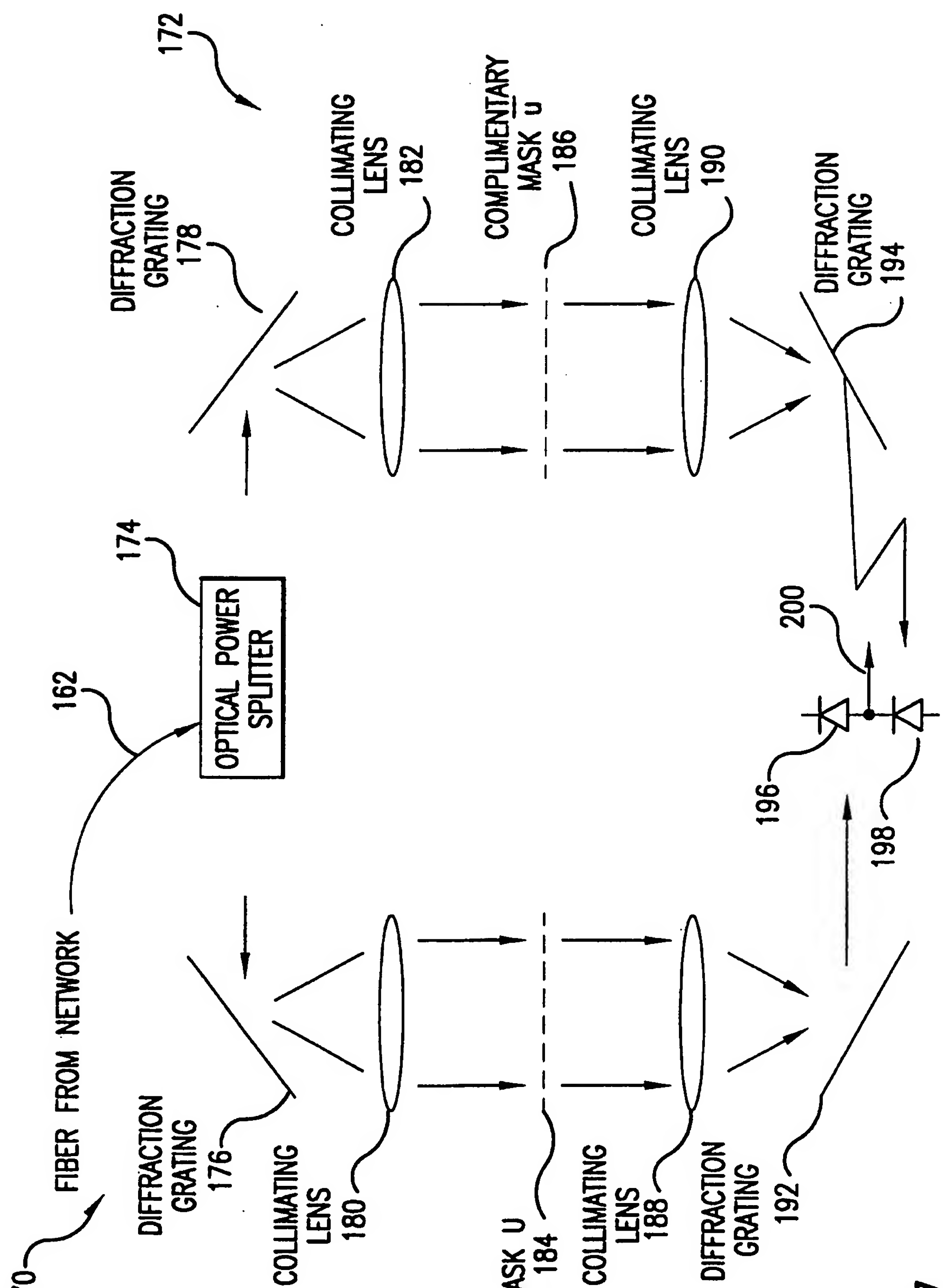

170
FIBER FROM NETWORK
162
OPTICAL POWER SPLITTER
174
172
DIFFRACTION GRATING 176
COLLIMATING LENS 180
MASK U 184
COLLIMATING LENS 188
DIFFRACTION GRATING 192
DIFFRACTION GRATING 178
COLLIMATING LENS 182
COMPLIMENTARY MASK $\bar{u}$ 186
COLLIMATING LENS 190
DIFFRACTION GRATING 194
196
198
200

FIG. 7

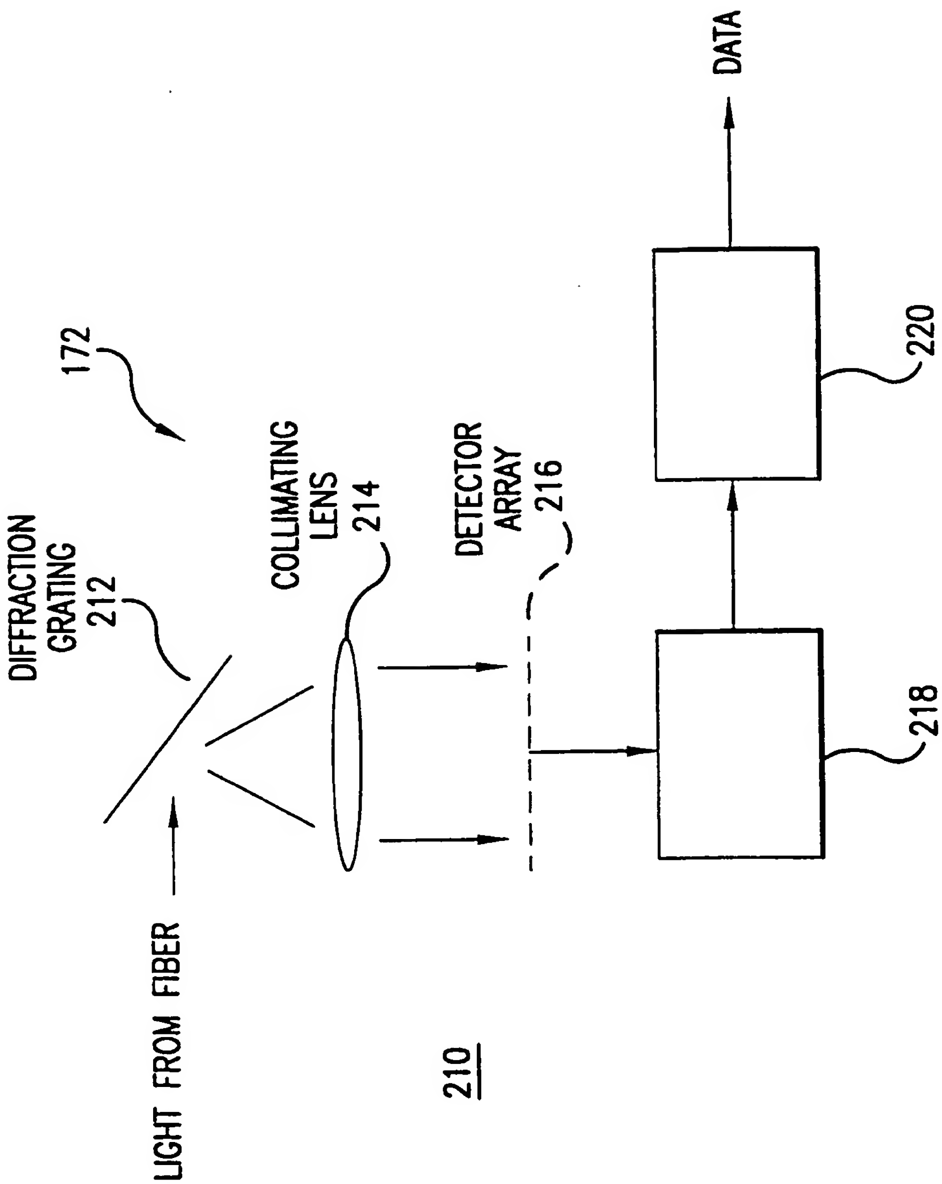

172
DIFFRACTION GRATING 212
COLLIMATING LENS 214
DETECTOR ARRAY 216
LIGHT FROM FIBER
218
220
DATA
210

FIG. 8

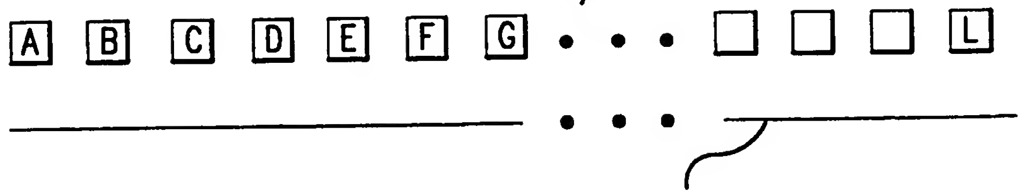


FIG. 9

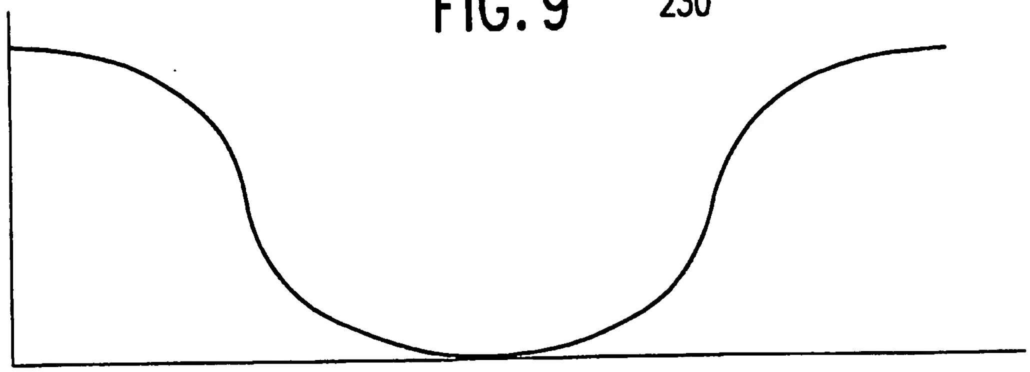


FIG. 10A

FIG. 10B

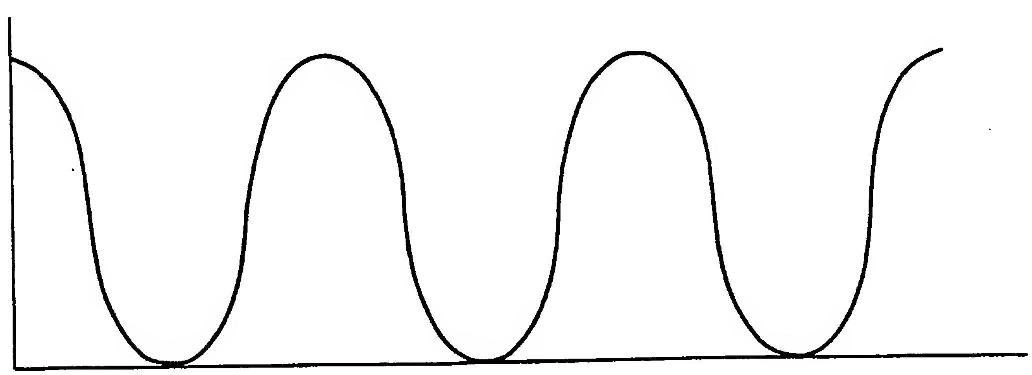


FIG. 10C

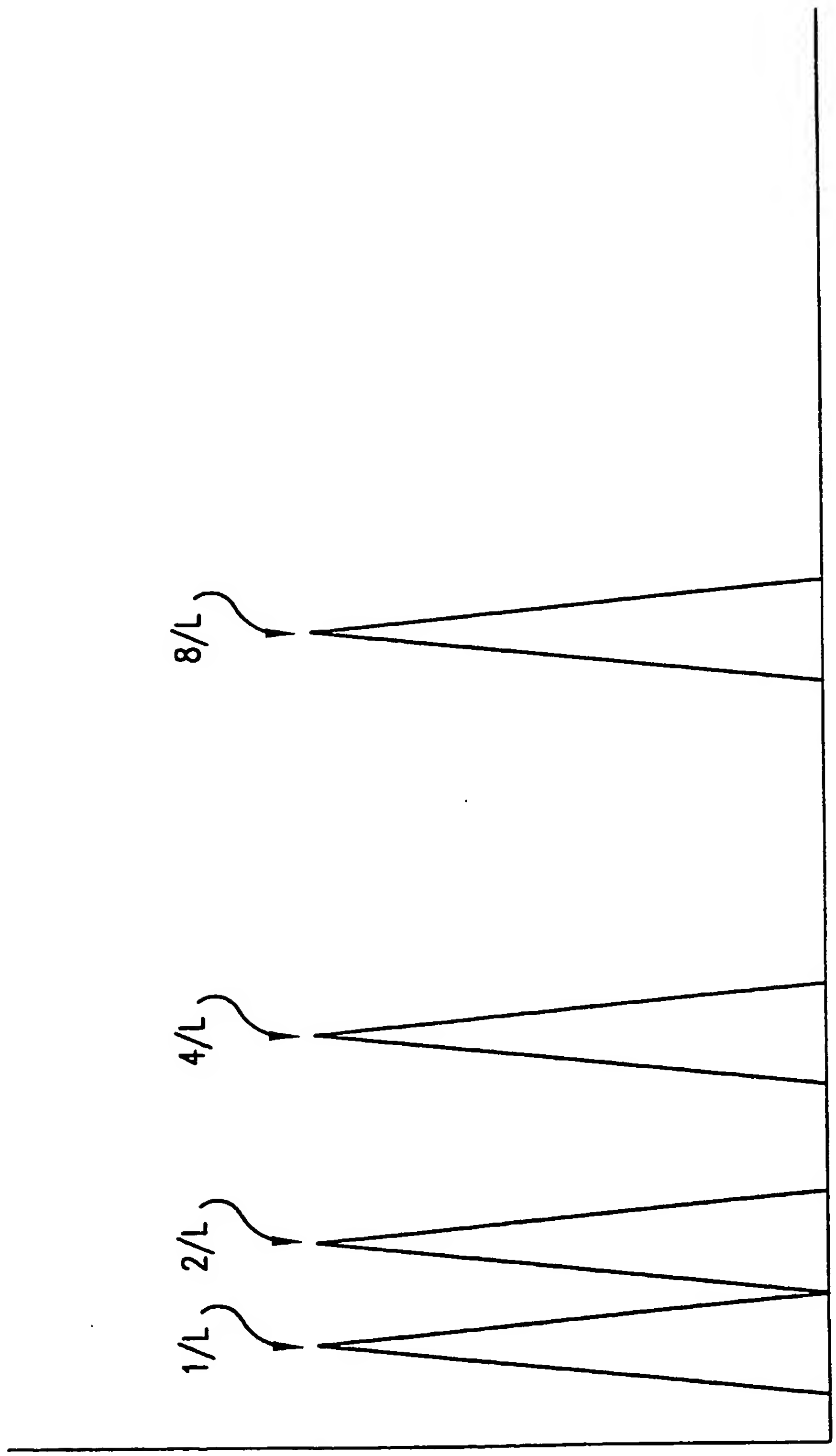


FIG. 11

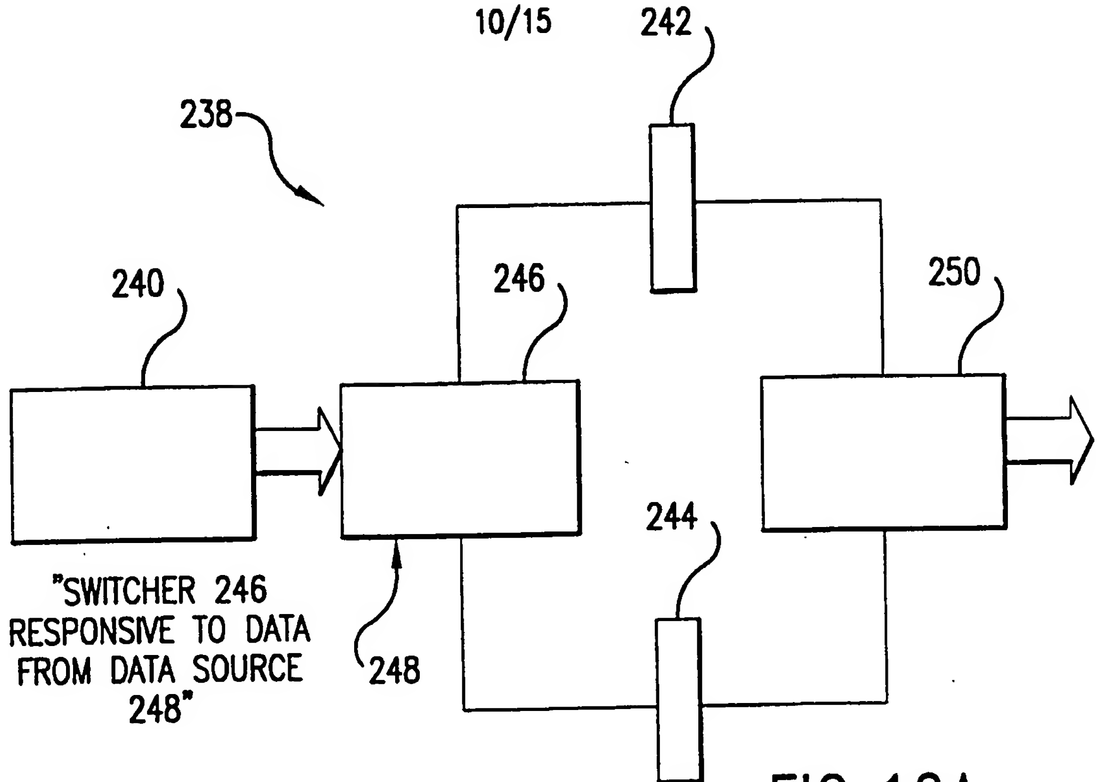


FIG. 12A

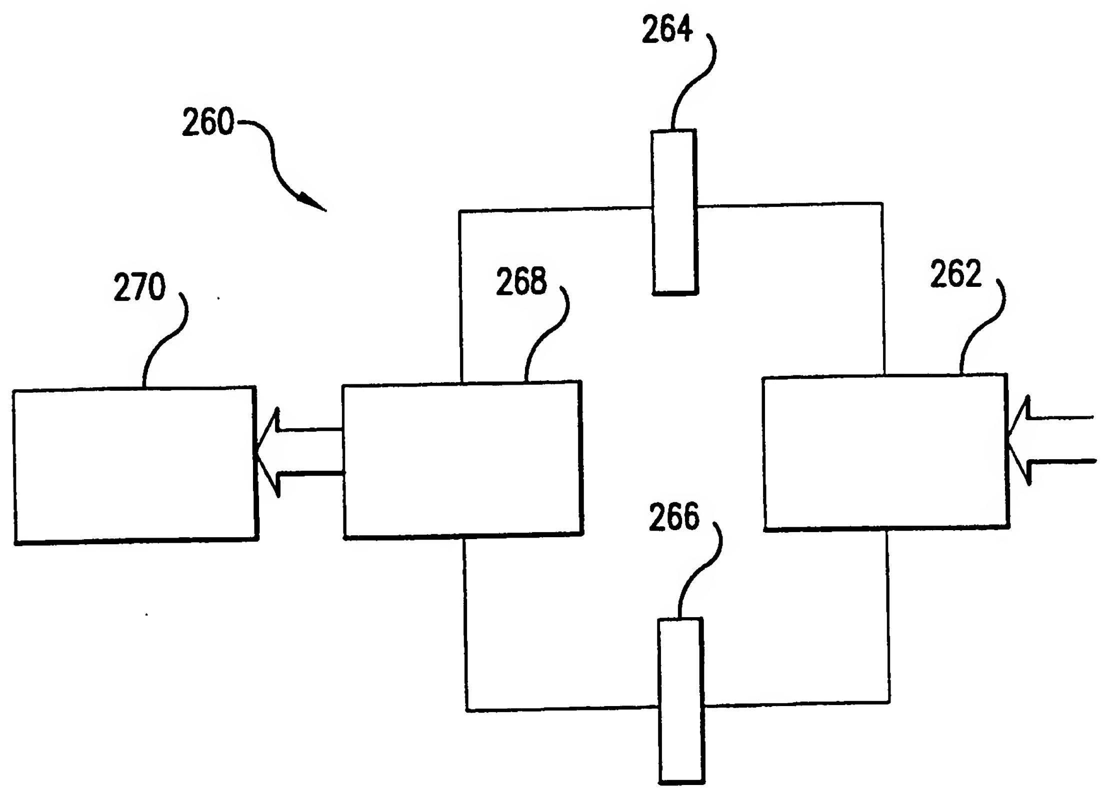


FIG. 12B

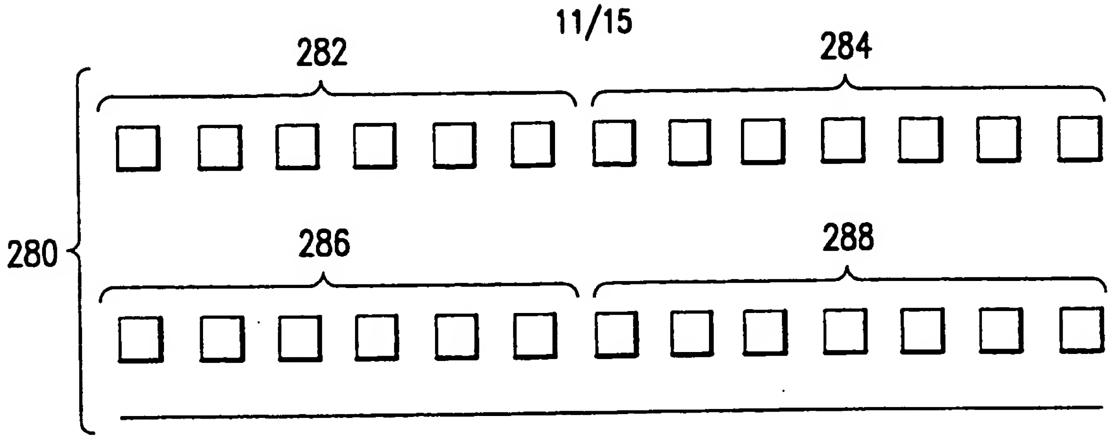


FIG. 13A

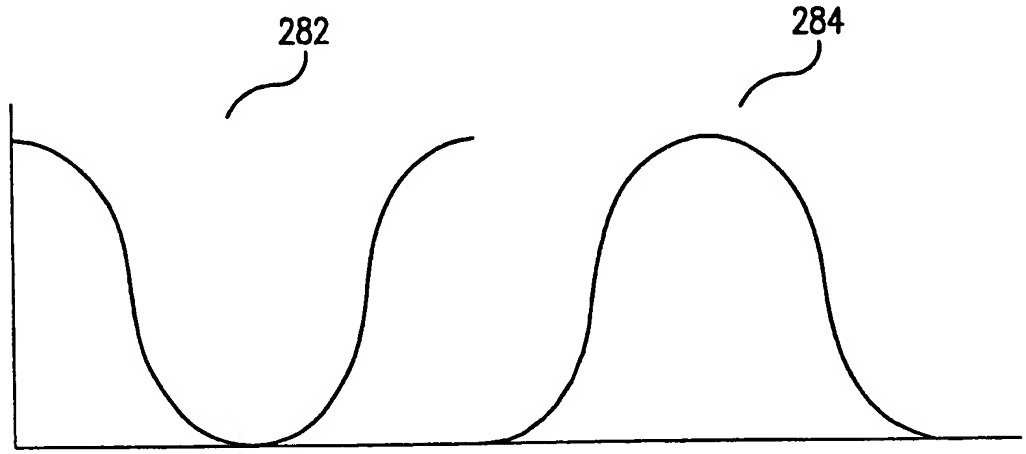


FIG. 13B

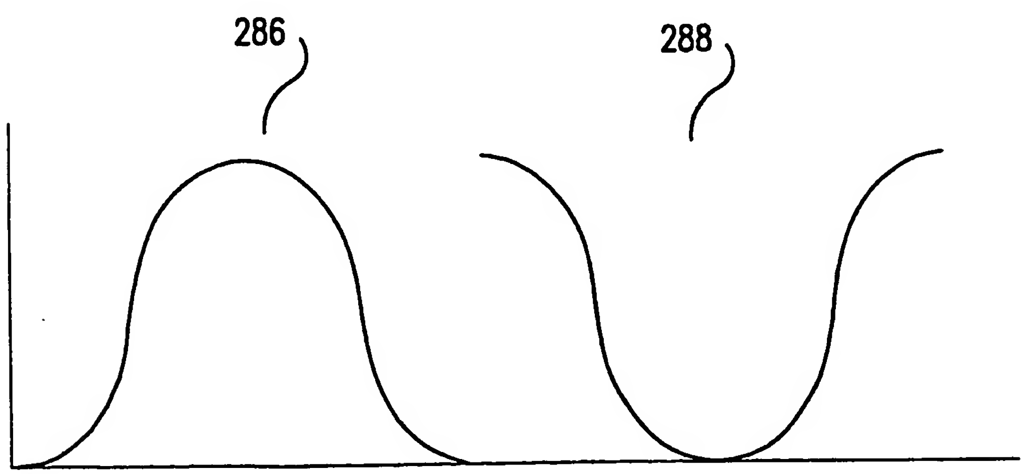


FIG. 13C

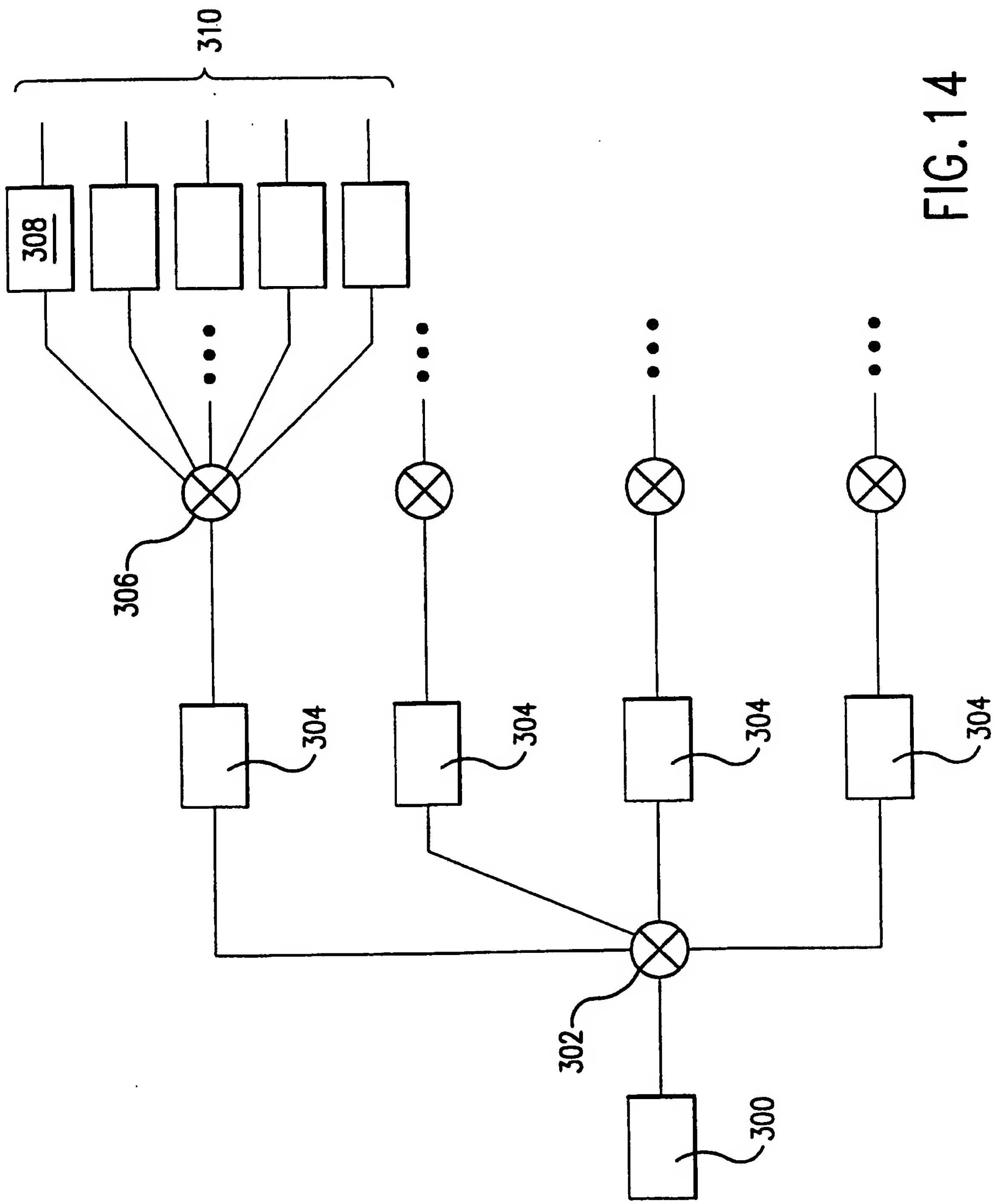


FIG. 14

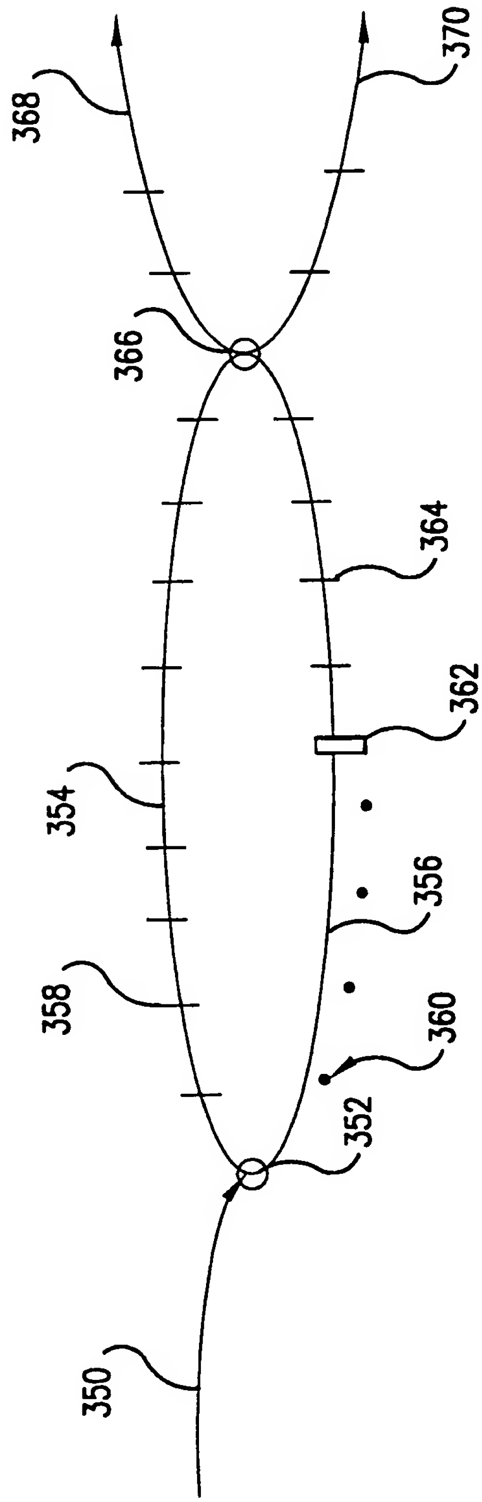


FIG. 15

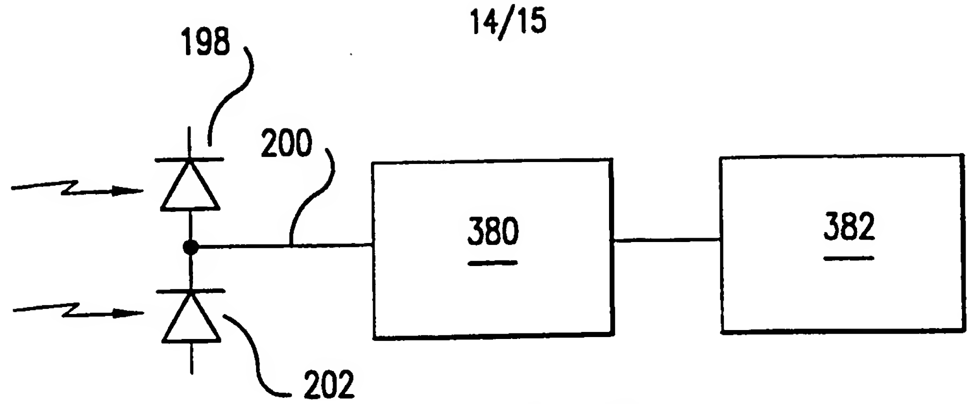


FIG. 16

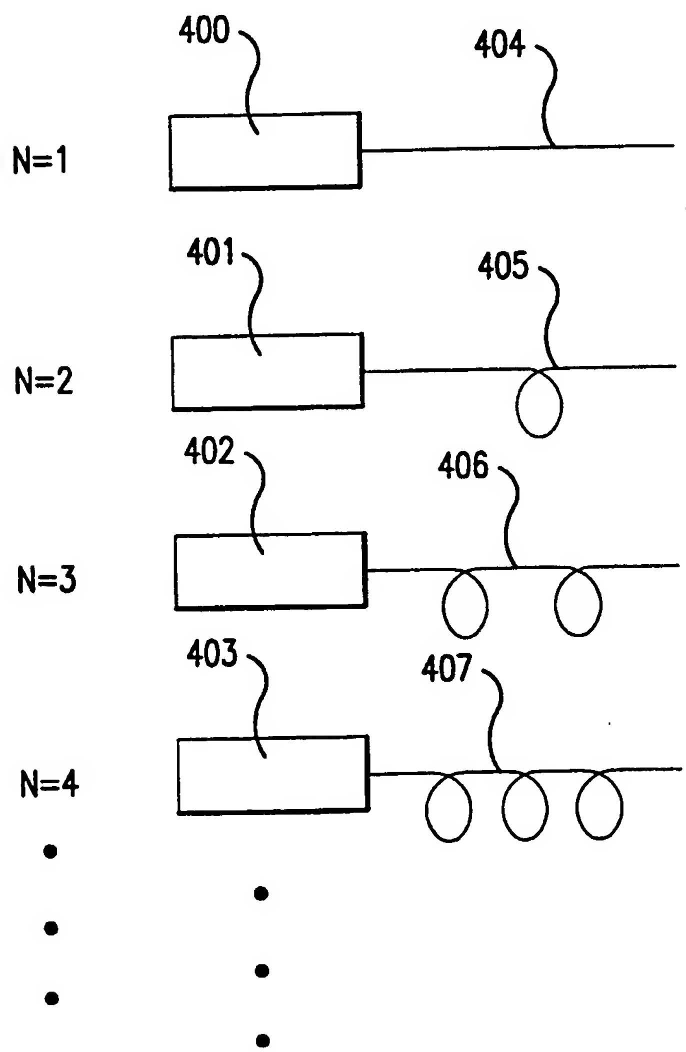


FIG. 17

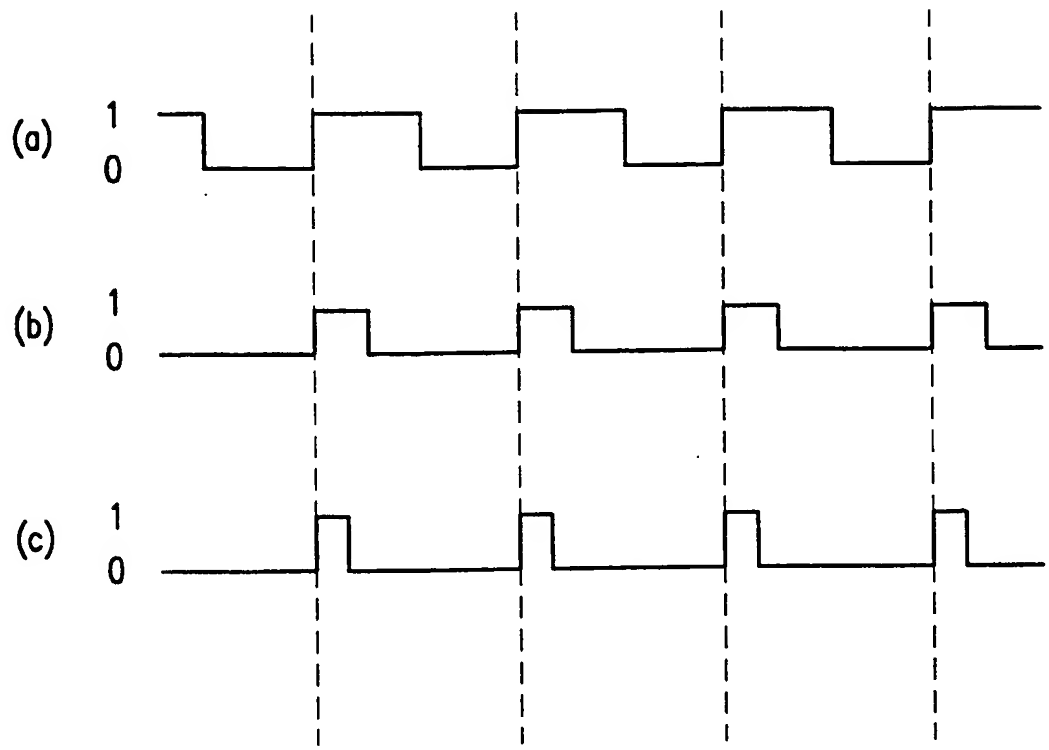


FIG. 18

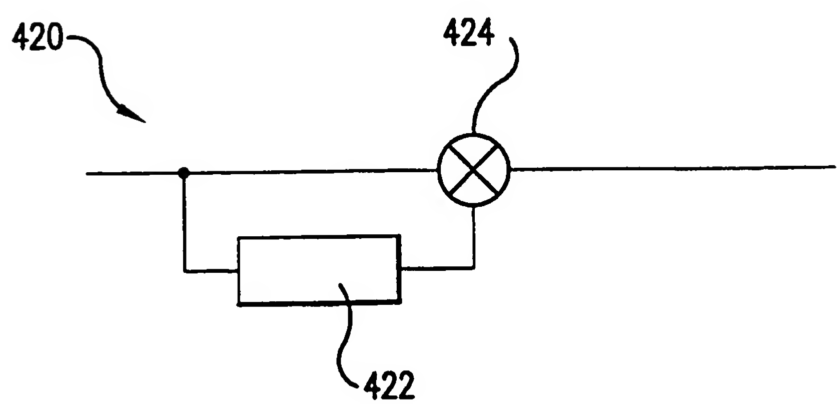


FIG. 19

INTERNATIONAL SEARCH REPORT

International Application No
PC./US 99/17258

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04J11/00 H04B10/155

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04J H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	O'FARRELL T ET AL: "CODE-DIVISION MULTIPLE-ACCESS (CDMA) TECHNIQUES IN OPTICAL FIBRE LANS" NATIONAL CONFERENCE ON TELECOMMUNICATIONS, YORK, 2 - 5 APRIL, 1989, no. CONF. 2, 2 April 1989 (1989-04-02), pages 111-115, XP000041177 INSTITUTION OF ELECTRICAL ENGINEERS ISBN: 0-85296-378-5 abstract	1
A	page 111, column 2, line 52 -page 112, column 1, line 9	8,10

	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 November 1999	24/11/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Chauvet, C

1

International Application No
PCT/US 99/17258

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
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